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CONTRACT REPORT BRL-CR-572

A LABORATORY RAILGUN FOR TERMINAL BALLISTICS AND ARC ARMATURE RESEARCH STUDIES

SPARTA, INC.
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US ARMY BALLISTIC RESEARCH LABORATORY
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A conceptual design was developed for a laboratory railgun suitable for both arc armature research and terminal ballistics studies. High utility and easy maintenance were the key design considerations. Parametric trade-off studies were conducted to evaluate and select the railgun parameters to achieve a system that can accelerate a 120 gm launch package to 2km/s. The design incorporates use of advanced materials for the bore components to minimize maintenance, and maximize performance through low bore erosion and deflection. The conceptual design includes features that allows easy replacement of the bore components for test evaluation; requires a minimum amount of manpower for assembly and operation; and has provision for the required test diagnostics.

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FINAL REPORT

A LABORATORY RAILGUN FOR TERMINAL BALLISTICS AND ARC ARMATURE RESEARCH STUDIES

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~~March~~, 1987
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PROJECT SUMMARY

The U.S. Army Ballistic Research Laboratory (BRL), as well as other terminal ballistic research and development facilities, require a high velocity projectile launcher capable of at least 5 shots per day, at higher peak/average acceleration, and lighter sabots than utilized with light gas guns. The electromagnetic railgun has the potential to meet these needs.

This report documents the results of a Phase I SBIR program that developed a conceptual design of a high utility, low maintenance railgun for primary use as a 1/4 scale high velocity terminal ballistics test bed. The gun would also be a tool for performing research on plasma armatures and their interaction with the bore. During the program, design requirements were established, performance and trade-off studies were conducted, material selections were made, design analyses were performed, the conceptual design drawings were developed, and the approximate system cost was estimated.

In order to assure that the required utility and performance would be achieved, the conceptual design has several innovative features including the utilization of high stiffness advanced ceramic bore and backup insulator materials to minimize elastic deflections; the application of an optimized preloading technique to assure maximum pre-compression at the bore interface; and the inclusion of erosion resistant bore surfaces with solid state bonded W claddings on the high strength $Cu\text{-}Al_2O_3$ rails and advanced Si_3N_4 tough, high strength ceramic bore insulators.

Additional features of the overall conceptual design included simplified assembly/disassembly, provisions for both plasma and projectile injection, and good access for diagnostic probes

The railgun is designed to accelerate a 120 gm launch package (sabot and projectile) to approximately 2200 m/s in a 4 m barrel. The injection velocity is 300 m/s with a light gas injector. The pre-accelerator barrel length was 1.5 m. The railgun is driven by a 4.5 MJ capacitor bank operating at 11 kV coupled to a 4.3×10^{-6} Henry pulse shaping coil inductor (time constant of 5 ms). The peak current achieved in the rails is approximately 1.2 MA.

1.0 INTRODUCTION

One of the critical elements of the U.S. Army's research and development effort is the study of high velocity (>1600 m/sec) projectiles and the penetration of these projectiles into armor. In this regard, BRL serves as the lead Army laboratory in ballistics technology, lethality evaluation, and ballistic validation of new technologies. Currently, the Laboratory utilizes light gas guns to launch high velocity projectiles. These devices are limited to one or possibly two shots per day and their relatively low pressure requires larger, heavier sabots. The BRL, as well as other terminal ballistic research and development facilities, require a high velocity projectile launcher capable of at least 5 shots per day at higher peak/average acceleration, and lighter sabots than utilized with light gas guns would be desirable. The electromagnetic railgun has the potential to meet these needs. However, significant innovation in the structural design approach and the utilization of advanced material concepts are required in order to achieve the necessary utility and to minimize maintenance requirements.

This report documents the results of a Phase I SBIR program to develop a conceptual design of a high utility, low maintenance railgun for primary use as a 1/4 scale high velocity terminal ballistics test bed. The gun would also be a tool for performing research on plasma armatures and their interaction with the bore. During the six months of the program, SPARTA, Inc. in conjunction with its subcontractor, Maxwell Laboratories, Inc. established the design requirements, conducted performance and trade-off studies, made material selections, performed design analyses, developed the conceptual design drawings and developed the approximate system cost.

1.1 The Railgun Environment

The environment in a railgun bore differs significantly from that of a conventional chemical gun. A railgun bore consists of two current carrying conductor rails separated by dielectric insulator spacers as shown schematically in Figure 1.1. The primary environmental factors include the plasma pressure, the electromagnetic rail repulsion force, joule heating in the rails and the plasma surface heat load. The barrel plasma pressure and the electromagnetic rail repulsion force cause both significant deformation of the bore (initially radially outward) and the breaking of the seal between the rail and the insulator spacer. These effects can result in permanent deformation or fracture of the rail and/or insulator as well as plasma leakage at their interface. Both of these deteriorate performance by permitting plasma blowby and/or excessive projectile/bore interaction. In addition, the interaction of the hot plasma with the bore surfaces causes ablation, melting and/or arc erosion of both the conductor rails and insulator spacer. A high utility, low maintenance experimental railgun must be designed to counter all of these effects, which decrease lifetime and performance and increase the need for intershot maintenance.

1.2 Design Approach

In order to assure that the required utility and performance would be achieved, the conceptual design effort was focused on minimizing plasma leakage, bore deflection and erosion. The conceptual design shown in Figure 1.2 was developed including the following key features:

- The utilization of high stiffness advanced ceramic bore and backup insulator materials to minimize elastic deflections

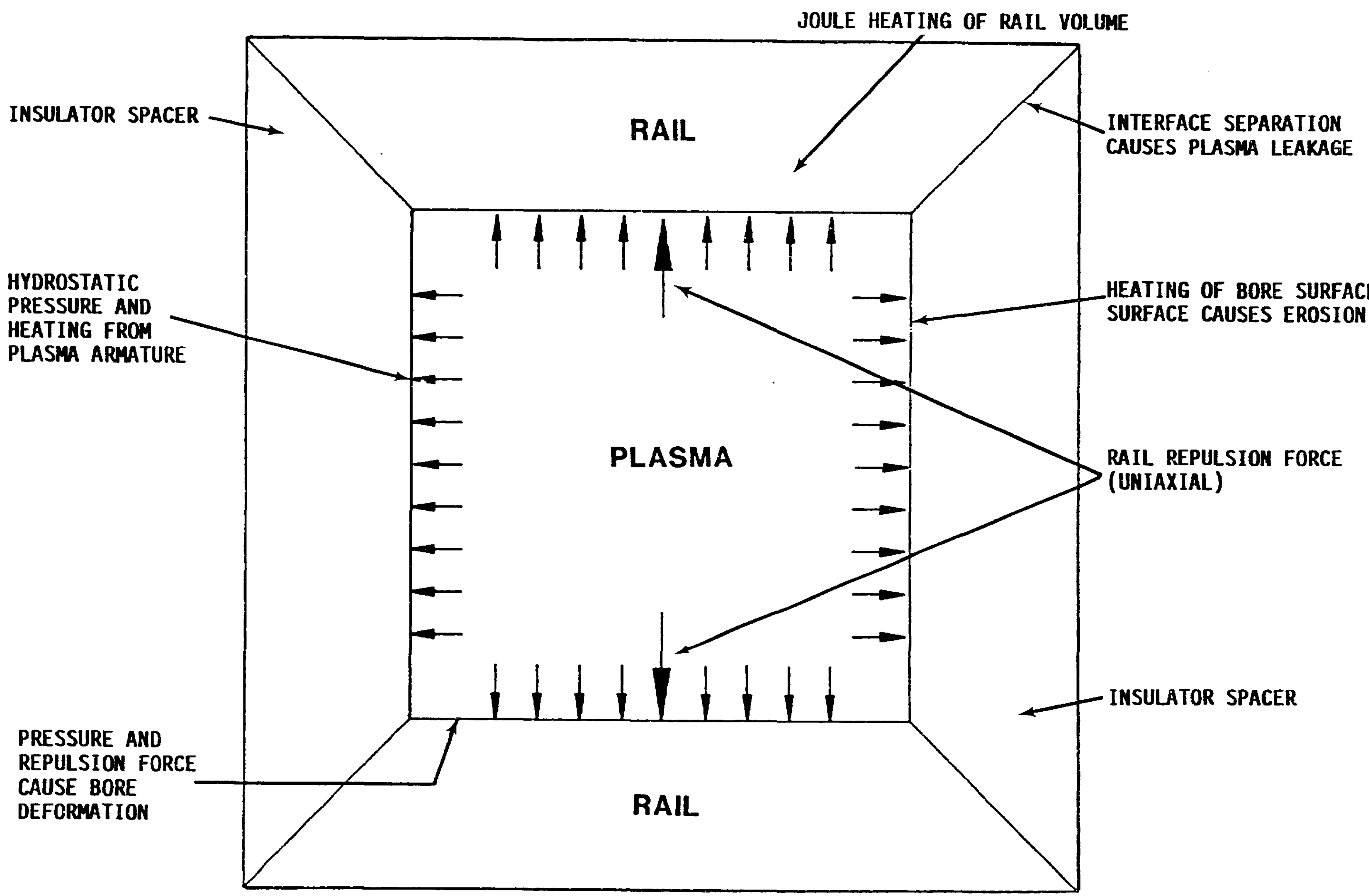

Figure 1.1. The Railgun Bore Environment Produces High Mechanical and Thermal Loading of the Rails and Insulator Spacers

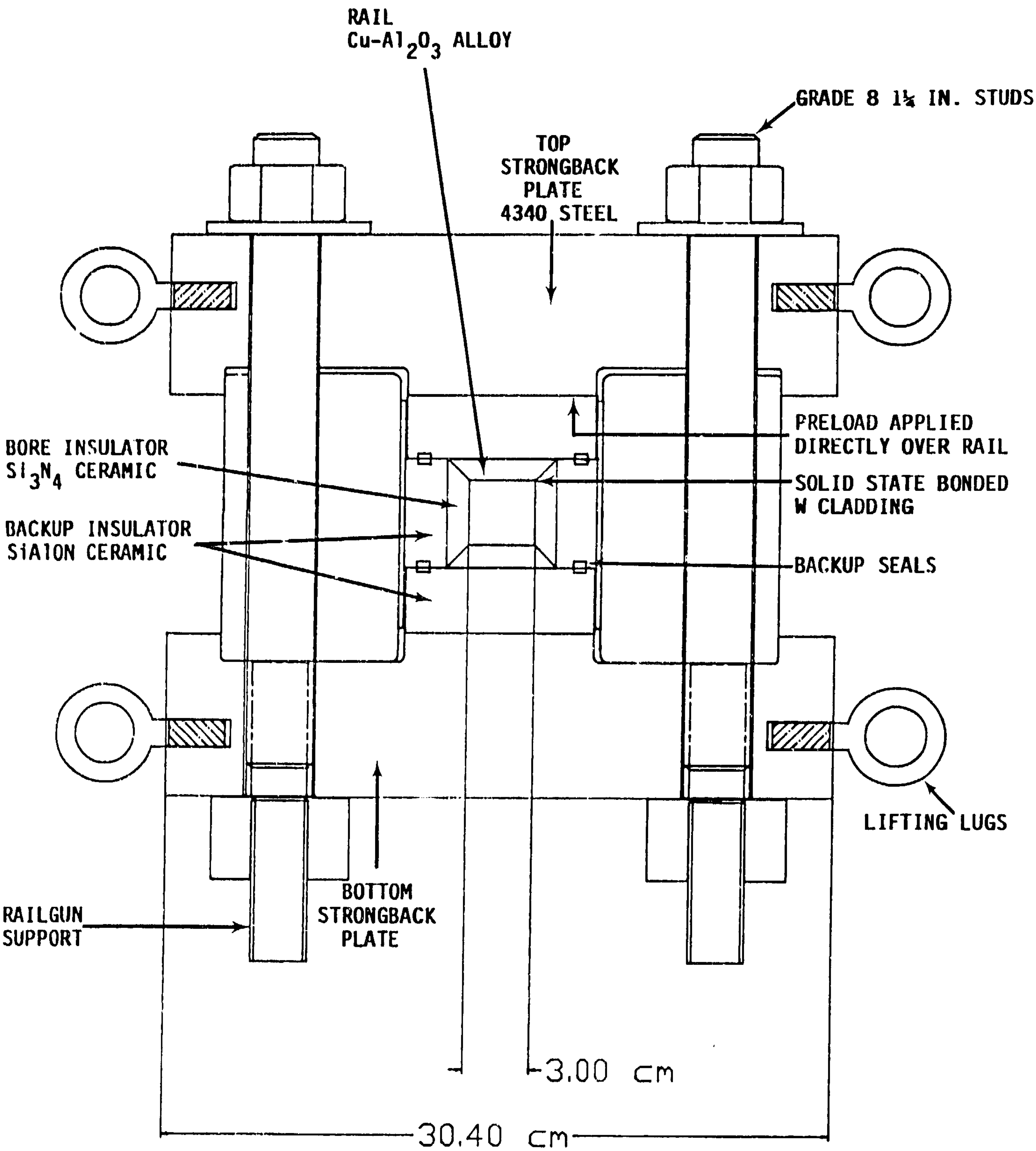

Figure 1.2 Conceptual Design for the BRL High Utility Railgun Using Advanced Materials and Optimized Preload Locations

- An optimized preloading technique to assure that the stud tensioning force is applied directly above the bore/insulator interface for maximum pre-compression at the bore interface

- Erosion resistant bore surfaces including solid state bonded W claddings on the high strength Cu-Al_2O_3 rails and advanced Si_3N_4 tough, high strength ceramic bore insulators. Previous railgun testing has indicated that this combination gave the best erosion/melting resistance of all materials tested.

Additional features of the overall conceptual design shown in Figure 1.3 include:

- Simplified assembly/disassembly
- Provision for both plasma and projectile injection
- Access for diagnostic probes

The railgun can accelerate a 120 gm launch package (sabot and projectile) to approximately 2200 m/s in a 4 m barrel. The injection velocity is 300 m/s and is based on a light gas injector with a fast acting (<1 ms) valve. The pre-accelerator barrel length is 1.5 m. The railgun is driven by a 4.5 MJ capacitor bank operating at 11 kV coupled to a 4.3 x 10^{-6} Henry pulse shaping coil inductor (time constant of 5 ms). The peak current achieved in the rails is approximately 1.2 MA.

The railgun has considerable design flexibility and can serve as both a 1/4 scale terminal ballistics test facility and an arc armature research tool. Because of the use of the advanced materials and the innovative preloading method, the operating conditions can be increased to higher bore pressures and correspondingly higher terminal velocities (~2500 m/s) with only minor design modifications (increased bank energy and modified pulse shaping coil design).

1.3 Design and Performance Goals

Table 1.1 provides a summary of the performance and design goals established by the Contract Technical Monitor for this Phase I program. The initial requirements were established for an arc armature laboratory railgun. However, as the Phase I program evolved the Contract Technical Monitor broadened the railgun mission to emphasize terminal ballistics studies. A comparison of the initial arc armature railgun design requirements and the final utility railgun requirements is provided in Table 1.1. The changes included increasing the bank energy from 2 MJ to 4.5 MJ and increasing the injection velocity.

2.0 PARAMETRIC ANALYSIS

A comprehensive study was conducted over the range of parameters of interest. This was accomplished using Maxwell's Railgun design code. This computer code provides a stepwise integration of the electrical and mechanical equations for a given design configuration and calculates the electrical performance. The model includes the effects of:

- Loss terms in the power supply and pulse shaping inductor
- Skin effect resistance in the rails
- Arc voltage
- Injection velocity

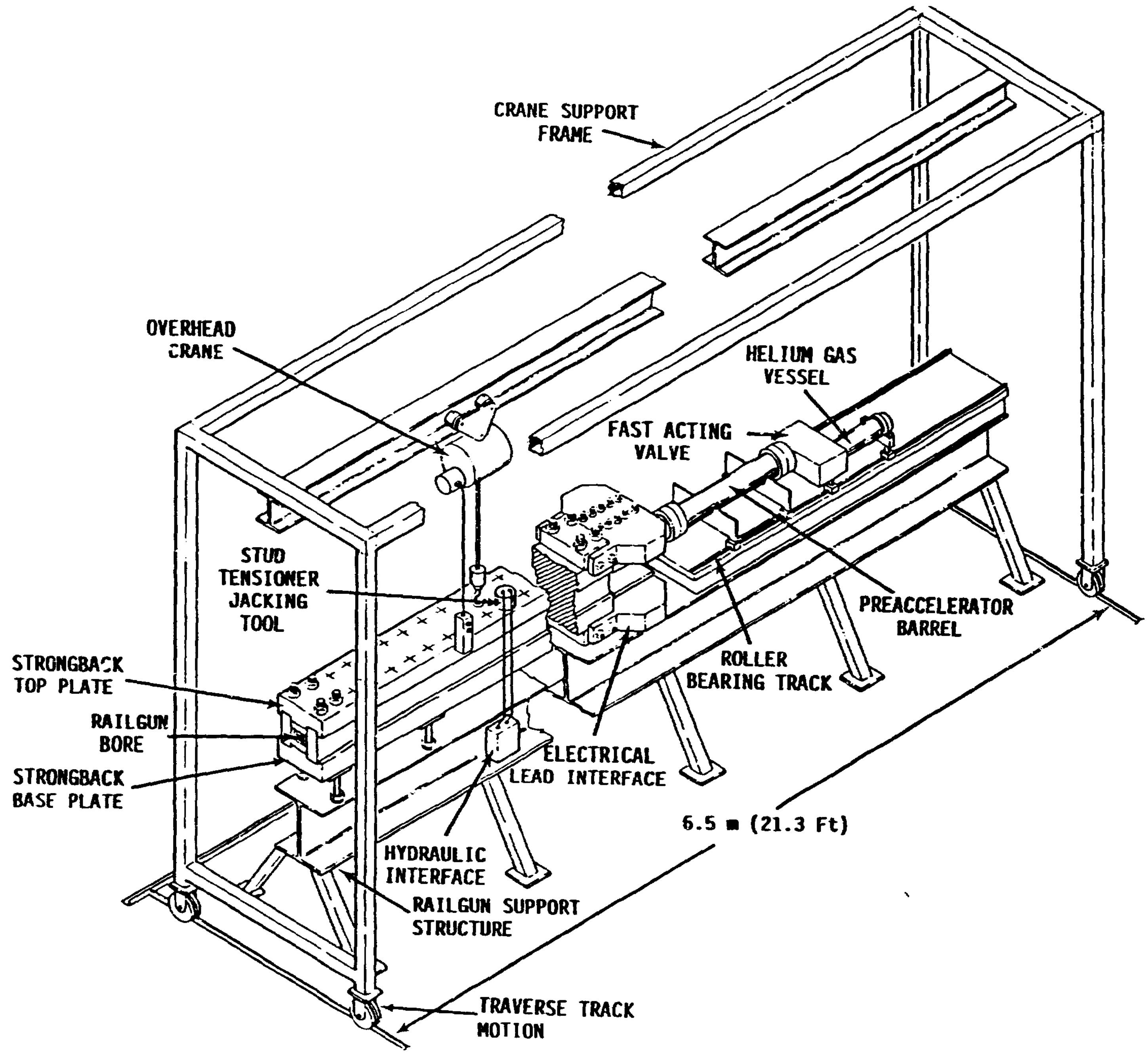

Figure 1.3 Isometric Drawing of the BRL High Utility Railgun Conceptual Design

- o Projectile/bore friction
- o Bore ablation
- o Air mass accelerated ahead of the projectile
- o Air drag due to shock waves inside and outside the barrel

The initial system trade-off studies focused on evaluating the overall effects of bore size, barrel length, injection velocity, projectile mass, and bank energy on final velocity and bore pressure. Table 2.1 provides the major design parameters and ranges of interest used in this trade-off study. In order to limit the trade-off parametric matrix to a reasonable size, projectile mass and bore size trade-offs were conducted at a constant bank energy. Facility interface parameters such as the capacitor bank voltage (11 kV) and the time constant (5 ms, L/R) were also held constant. After the preliminary evaluations of the trade-off studies were made, a detailed calculation was conducted for the selected design parameters to establish the baseline performance and design conditions.

TABLE 1.1. Design Requirements and Features for the Railgun Phase I Study

	Arc Armature Railgun	Utility Railgun
Bank Energy	<2 MJ Mate to MLI Bank	<4.5 MJ
Bank Voltage	11 kV	11 kV
Bore Size	2.5 - 3.5 cm	3.0 - 3.5 cm
Bore Shape	Square	Square
Injection Velocity	>300 m/s	>300 m/s
Exit Velocity	>2 km/s	>2 km/s
Launch Package	100 gms	120 - 150 gm
Inductor	2×10^{-6} H	4.3×10^{-6} H

Features

- o High utility (minimum intershot maintenance)
- o Simultaneous injection of plasma and projectile.
- o Multiple shots without bore replacement (long life bore)
- o Easy replacement of bore components (minimum time and number of men for assembly/disassembly)
- o Easy access for bore diagnostics

The preliminary performance requirements of achieving greater than 2 km/s exit velocity for relevant sabot and projectile launch package masses drove the system study in the direction of higher bank energy, larger bore diameter, and higher bore pressures.

TABLE 2.1. Major Design Parameters for BRL Railgun Trade-Off Study

Parameter	Range
Bank Energy	2, 3, 4, 4.5 MJ
Projectile Mass	80, 150, 205 gm
Rail Height	2.5, 3, 3.5 cm
Bore Pressure	40 - 60 ksi

Figures 2.1 and 2.2 illustrate (for a constant bore diameter) the variation of the calculated final velocity and rail length for the projectile mass and bank energy ranges evaluated for the BRL railgun study. In order to achieve an exit velocity of 2 km/s bank energies of greater than 3 MJ and launch package masses between 100 to 150 gm are necessary. The corresponding railgun length falls in the range of 3 to 5 m.

Figures 2.3 and 2.4 show the parametric sensitivity of exit velocity (at constant bank energy of 3 MJ) to bore pressure (40, 60 and 80 ksi) and rail height for projectile masses of 80 gm (Figure 2.3) and 150 gm (Figure 2.4). The ability to operate near 2 km/s, and at reasonable bore pressure (40 - 60 ksi range) drives the selection of bore diameter to approximately 3 cm.

The exit velocity sensitivity to the injection velocity and launch mass is provided in Figure 2.5. A 300 m/s incremental increase (from 300 m/s to 600 m/s) shows approximately a 200 m/s incremental increase in the exit velocity. The selection of the injection velocity is dependent on the method of injection (burst disc or fast acting valve). High injection velocity (>500 m/s) can be obtained with the burst disc, whereas the fast acting valve may be limited to injection velocities below 500 m/s.

The bore pressure sensitivity to the pulse shaping coil inductance and bore size was also evaluated and is shown in Figure 2.6. The bore pressure selected for the baseline design was 45 ksi (300 MPa). This corresponded to a pulse shaping coil inductance of 4.3 microHenries for the 3 cm bore and 6.2 microhenries for the 2.5 cm bore, respectively. The sensitivity of the projectile exit velocity to inductance, bore size, and projectile mass is illustrated in Figure 2.7. The 3 cm bore operating at 45 ksi bore pressure and having a pulse shaping coil inductance of 4.3 microHenries provides exit velocities in the 2000-2200 m/s range depending on the launch package weight.

2.1 Evaluation and Selection of Baseline Design

The parametric trade-off studies were reviewed with the Contract Technical Monitor. This review, coupled with new changes in the design requirements, resulted in the final selection of the baseline design point. The baseline design parameters are given in Table 2.2. The selected design included a bank energy of 4.5 MJ, bore diameter of 3 cm, injection velocity of 300 m/s, and a time constant (L/R) of 5 ms. The launch package mass was taken at 120 gm for the performance analysis. This provides a reasonable margin for the design of a sabot to carry a 65 gm projectile. The bore pressure was taken as 45 ksi which is in the range of several operational railguns. The extension to higher bore pressures however, can be achieved because of the use of advanced materials and the innovative bore design configuration. These factors will be discussed in detail in Section 3.

The resulting final velocity for the 120 gm launch package is 2188 m/s. The variation of the projectile velocity with time and rail position is provided in Figure 2.8 and 2.9.

The time history of the current trajectory is provided in Figure 2.10. The peak current of 1.16 MA occurs approximately 0.8 ms into the pulse. The bore pressure loading profile illustrated in Figure 2.11 shows the peak pressure of 45 ksi (300 MPa) is experienced at approximately .5 m from the breech end. This value falls off to approximately 7 ksi (50 MPa) at the muzzle rail position. The peak value was utilized, however, along the entire

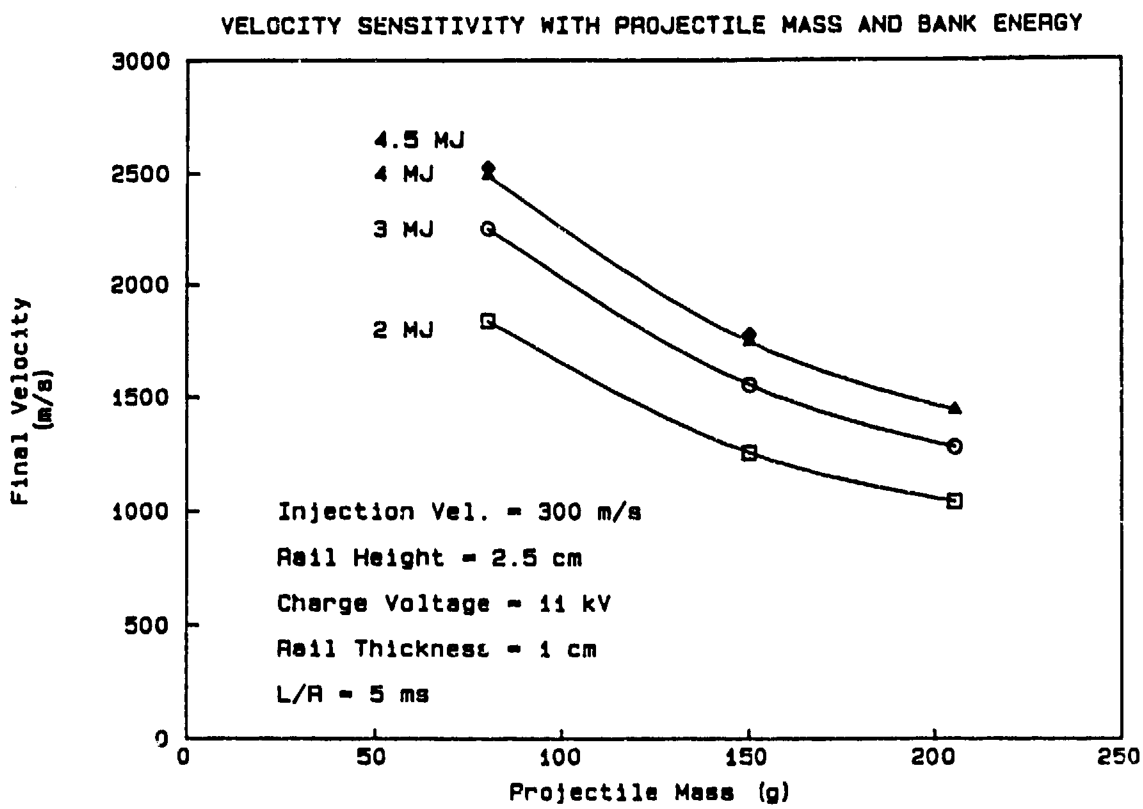

Figure 2.1. Velocity Sensitivity with Projectile Mass and Bank Energy

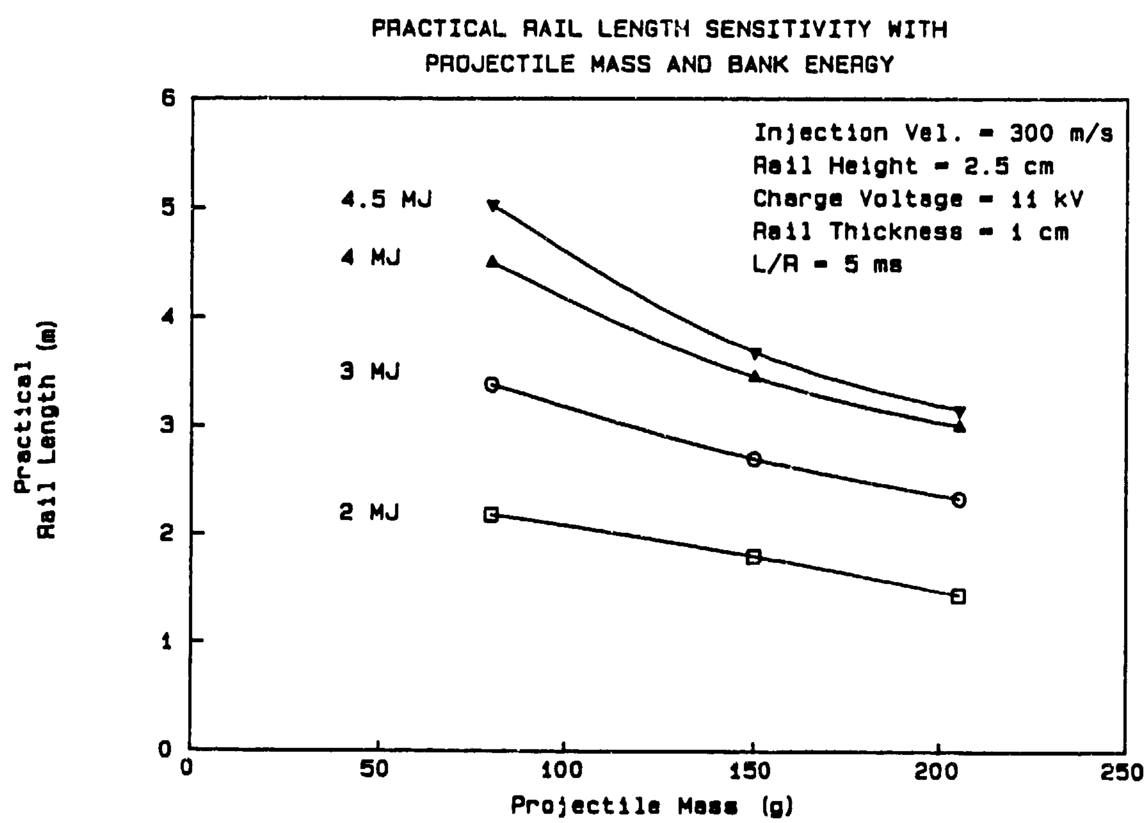

Figure 2.2. Practical Rail Length Sensitivity with Projectile Mass and Bank Energy

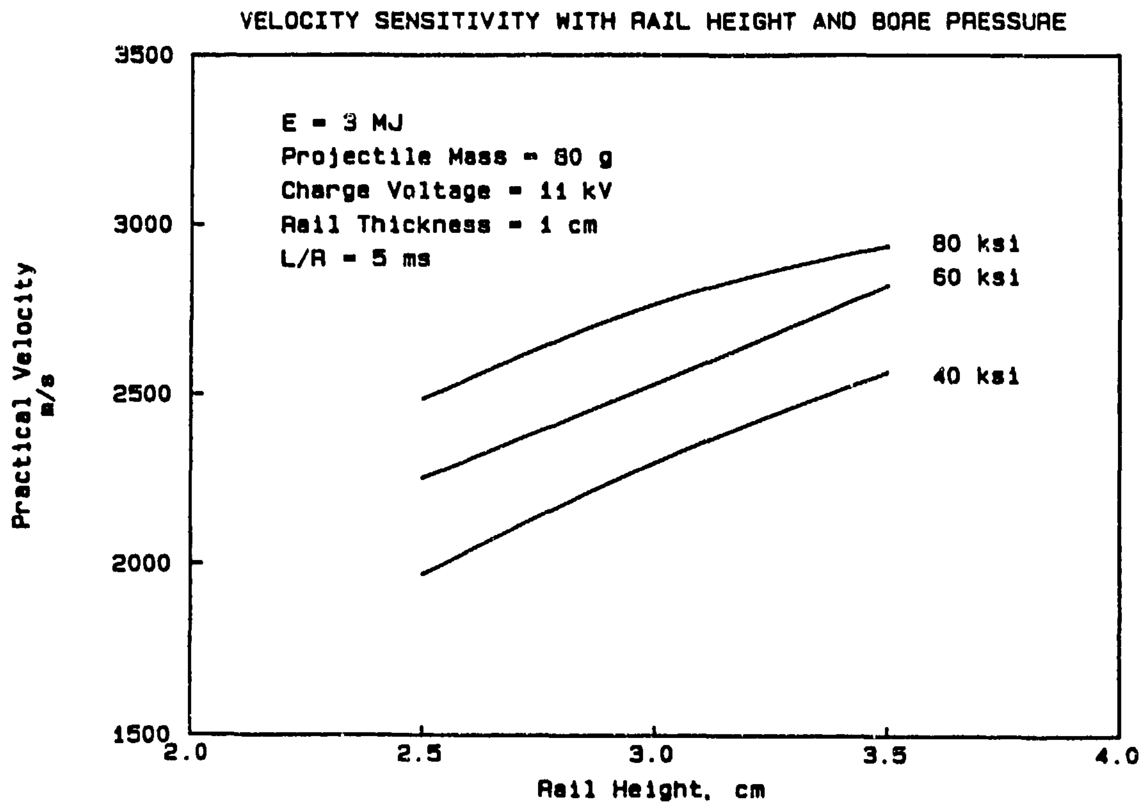

Figure 2.3. Velocity Sensitivity with Rail Height and Bore Pressure for a 80 gm Launch Package Mass

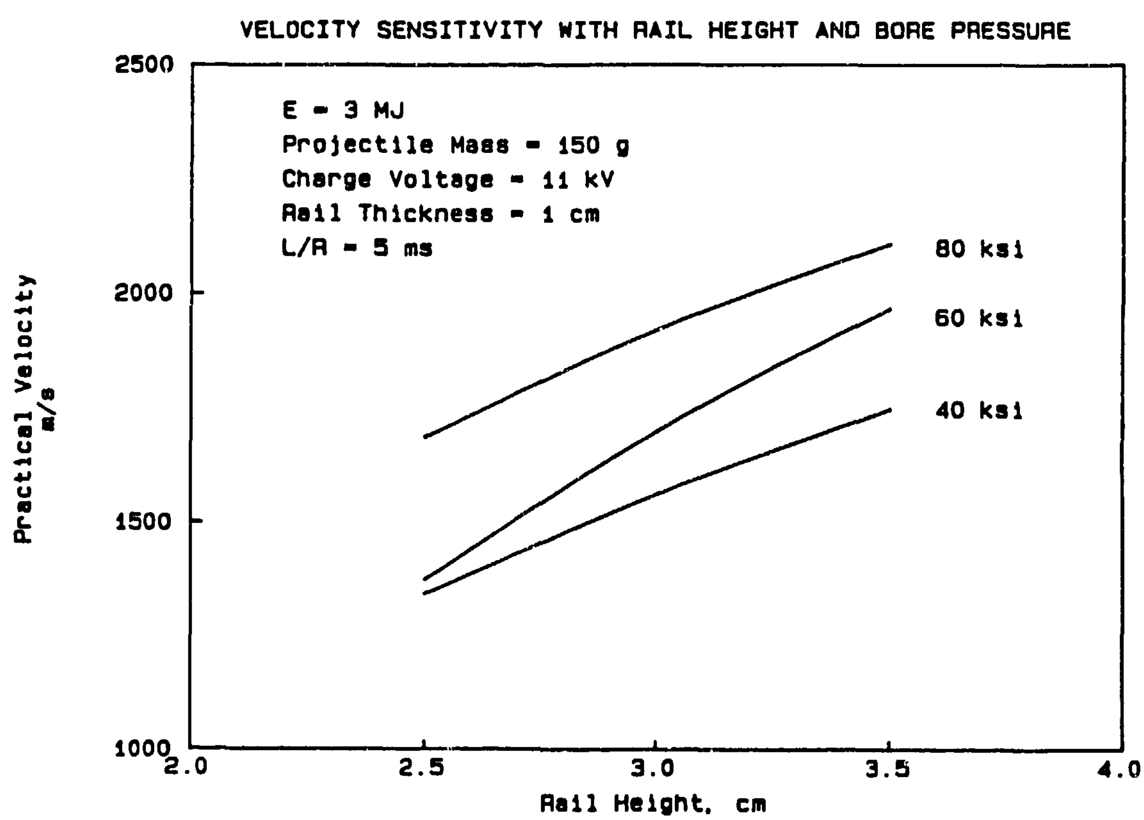

Figure 2.4. Velocity Sensitivity with Rail Height and Bore Pressure for a 150 gm Launch Package Mass

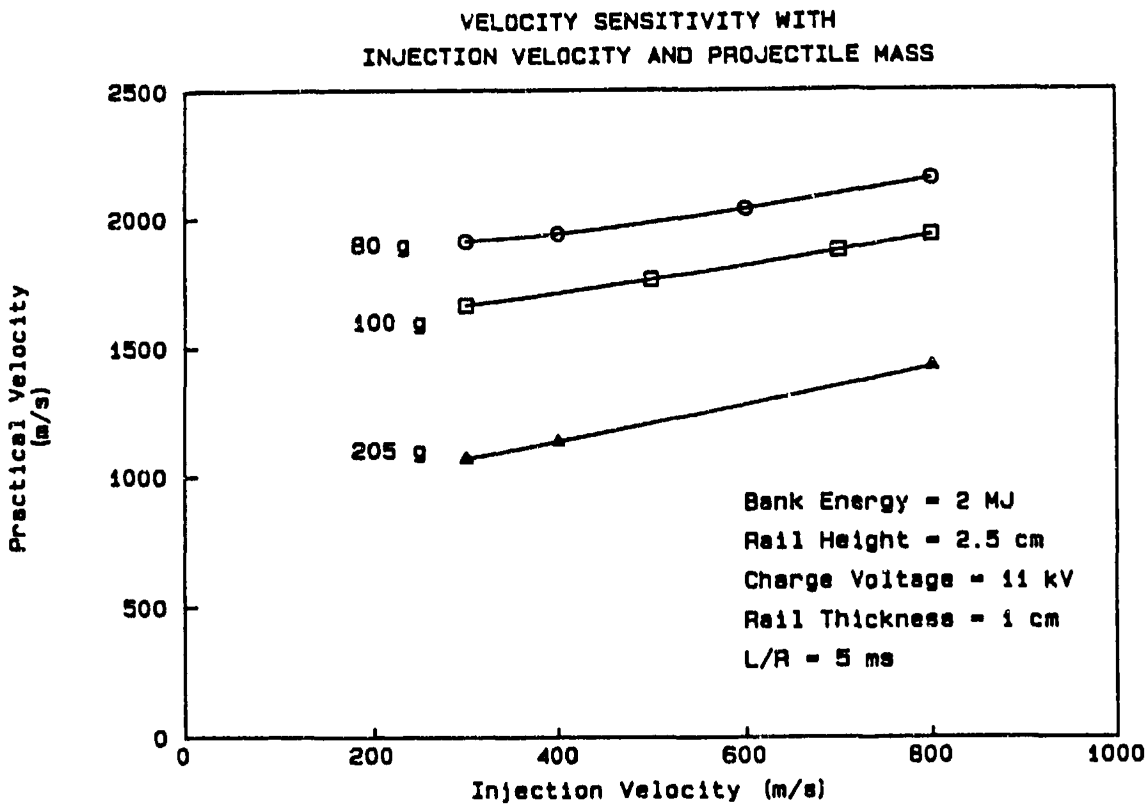

Figure 2.5. Exit Velocity Sensitivity with Injection Velocity and Projectile Mass

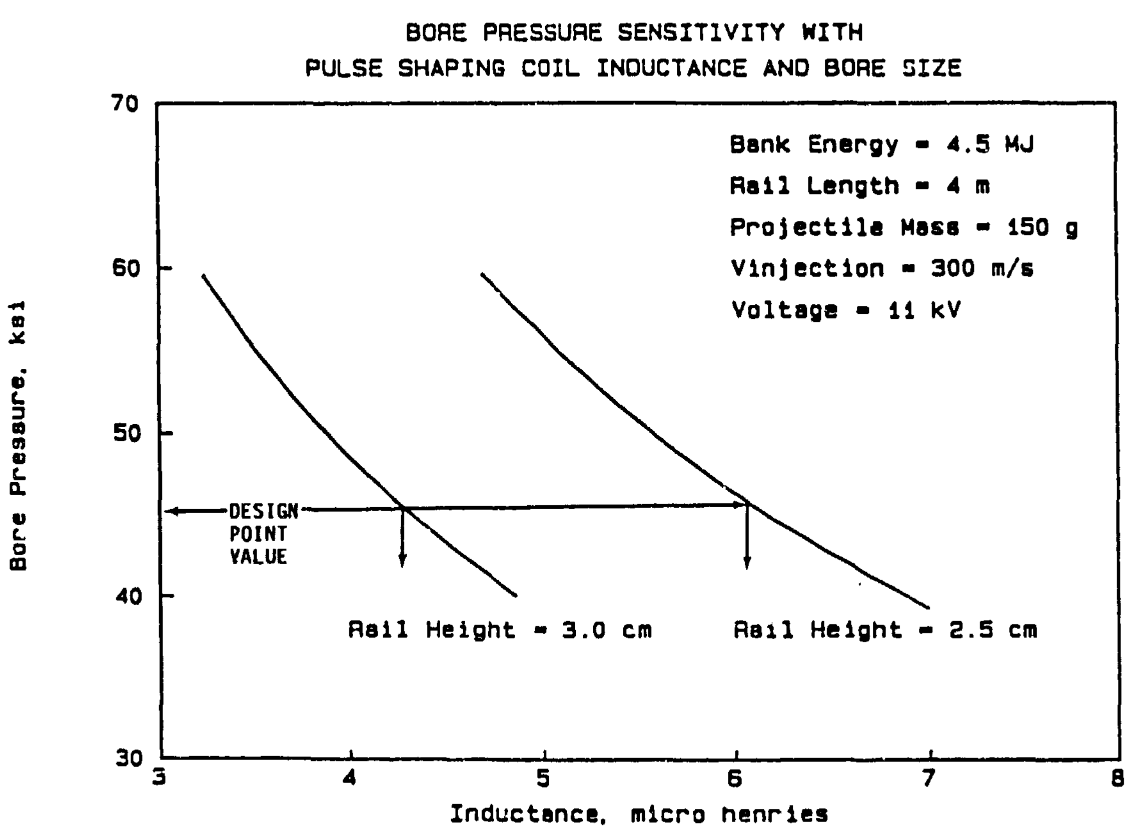

Figure 2.6. Sensitivity of Bore Pressure to Pulse Shaping Coil Inductance and Bore Size

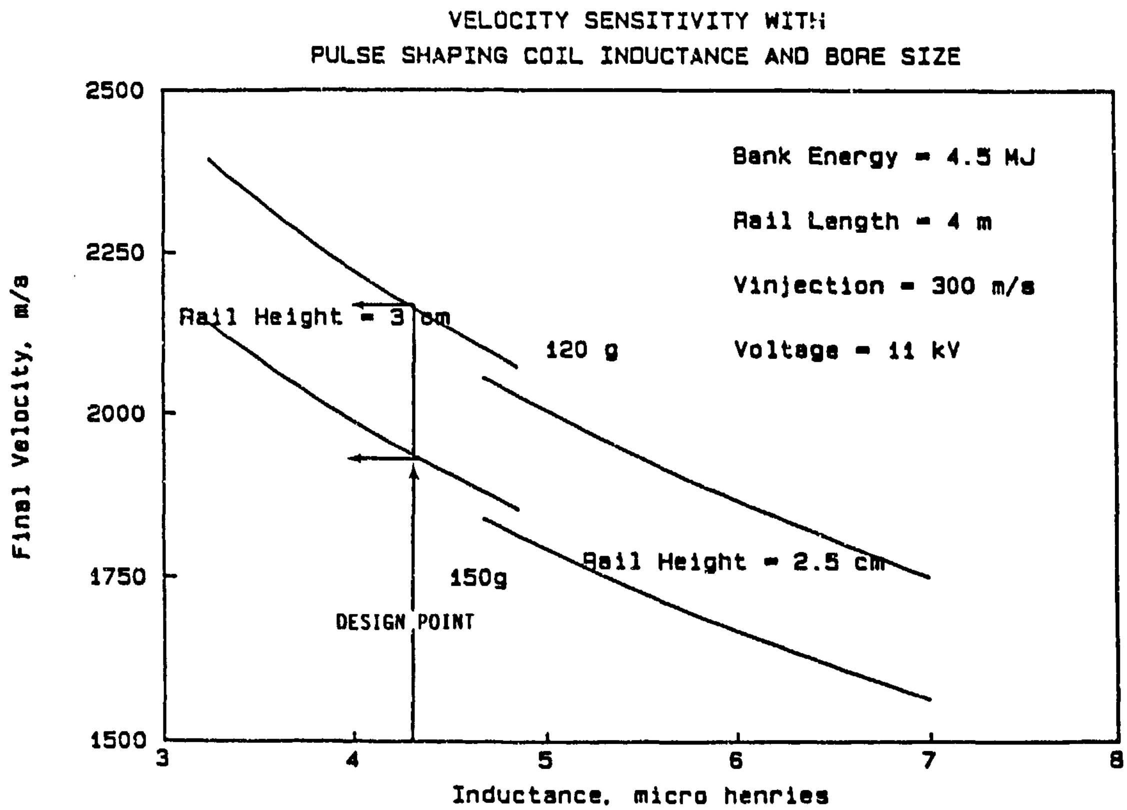

Figure 2.7. Sensitivity of Exit Velocity to Pulse Shaping Coil Inductance, Bore Size, and Projectile Mass

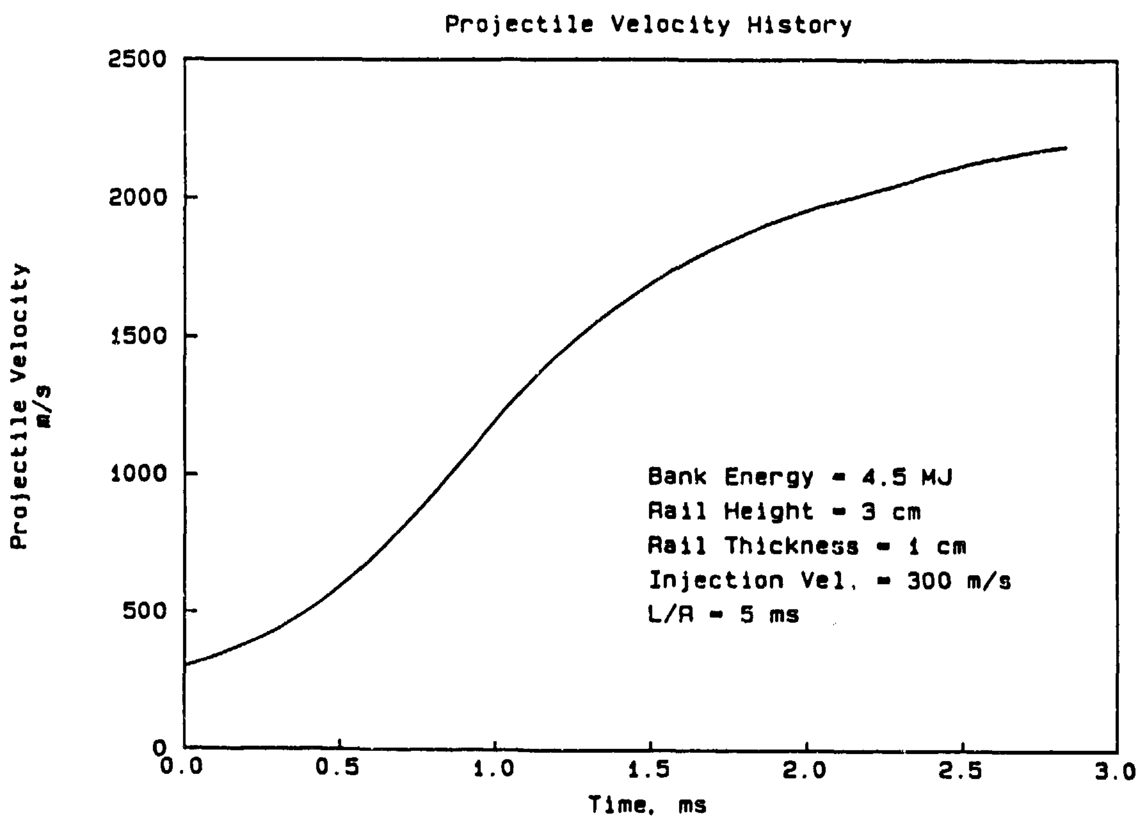

Figure 2.8. Baseline Design Projectile Velocity History

TABLE 2.2. Selected Baseline Design Point for the BRL Railgun

Railgun Calculation (Maxwell Code)

1.	Delta T for Calculation (sec)	1.0×10^{-6}
2.	Total Store Energy (joules)	4.50×10^{6}
3.	Charge Voltage (volts)	1.10×10^{4}
4.	Inductance LS (henries)	4.33×10^{-6}
5.	Resistance RS (ohms)	8.66×10^{-4}
6.	Inductance Derivative DL/DX	4.0×10^{-7}
7.	Arc Voltage (volts)	4.0×10^{2}
8.	Initial Velocity (meters/sec)	3.0×10^{2}
9.	Initial Mass (kg)	1.2×10^{-1}
10.	Length of Gun (m)	4.0
11.	Length of Flight (m)	1.0
12.	Friction Factor F	3.0×10^{-1}
13.	Bank Inductance (henries)	2.78×10^{-8}
14.	Bank Resistance (ohms)	4.56×10^{-4}
15.	Ablation Factor Alpha (kg/joule)	1.0×10^{-8}
16.	Percentage Copper Conductivity (%)	8.0×10^{1}
17.	Rail Height (m)	3.0×10^{-2}
18.	Rail Thickness (m)	1.0×10^{-2}
19.	Yield Current (amps)	5.7×10^{5}
20.	AP Projectile Areas (Meters**2)	9.0×10^{-4}
21.	Ambient Pressure (PA)	1.0×10^{5}
22.	Beta, Air Loading (kg/m)	1.17×10^{-3}
23.	C, Drag Factor	5.0×10^{-1}

Efficiency (%)	6.71
Final Mass	1.28×10^{-1}
Ablated Mass	8.43×10^{-3}
Int (.5*Vel^2*MDOT)	9.28×10^{3}
Kinetic Energy Added	3.01×10^{5}

Energy Edit at Time Projectile Leaves the Gun

C Bank (3 Terms)	5.73×10^{5}	12.7%
Inductor	4.76×10^{5}	10.6%
Resistor	2.15×10^{6}	47.8%
L Dot	4.5×10^{5}	10.1%
Arc Voltage	8.43×10^{5}	18.7%
Total	4.5×10^{6}	
Initial	4.5×10^{6}	

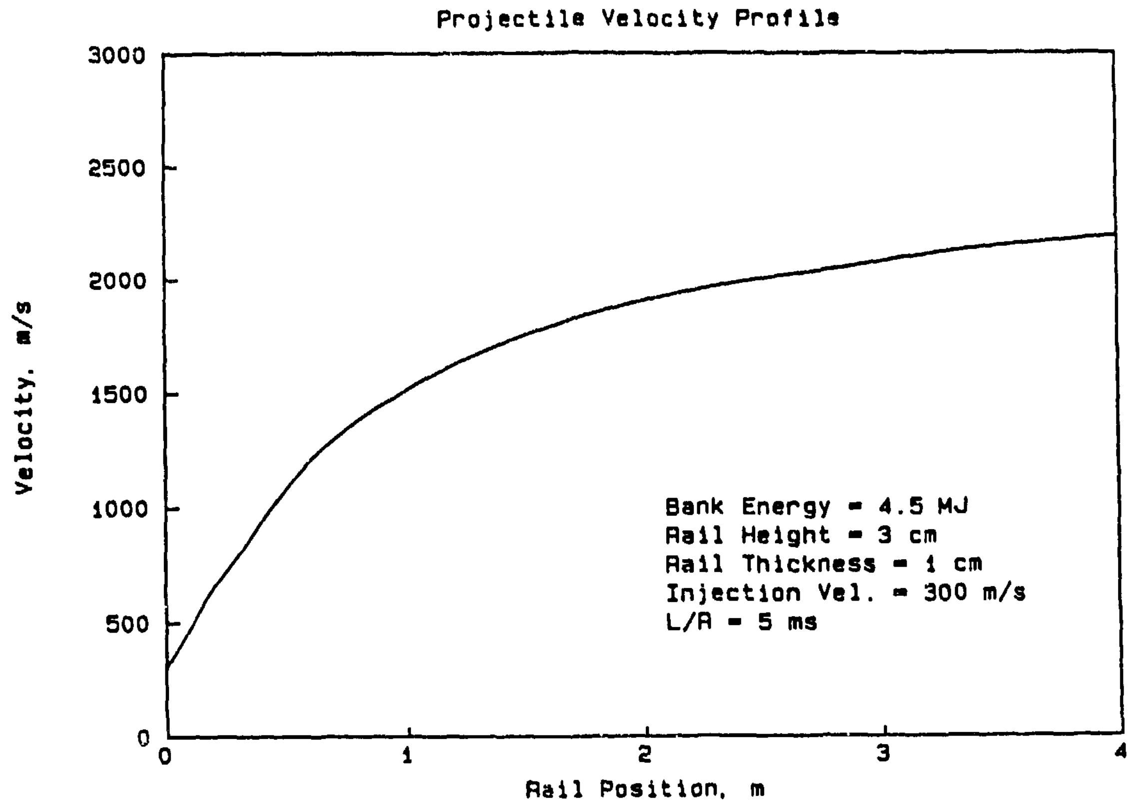

Figure 2.9. Baseline Design Projectile Velocity Profile

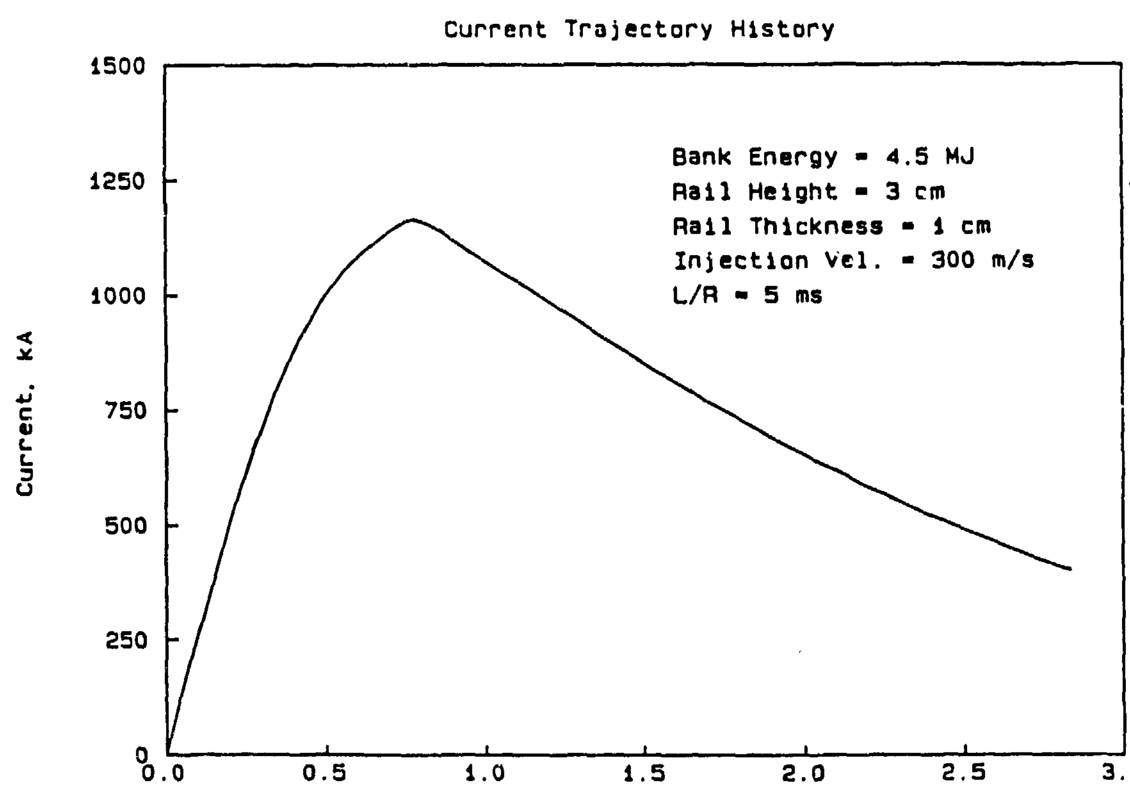

Figure 2.10. Baseline Design Current Trajectory History

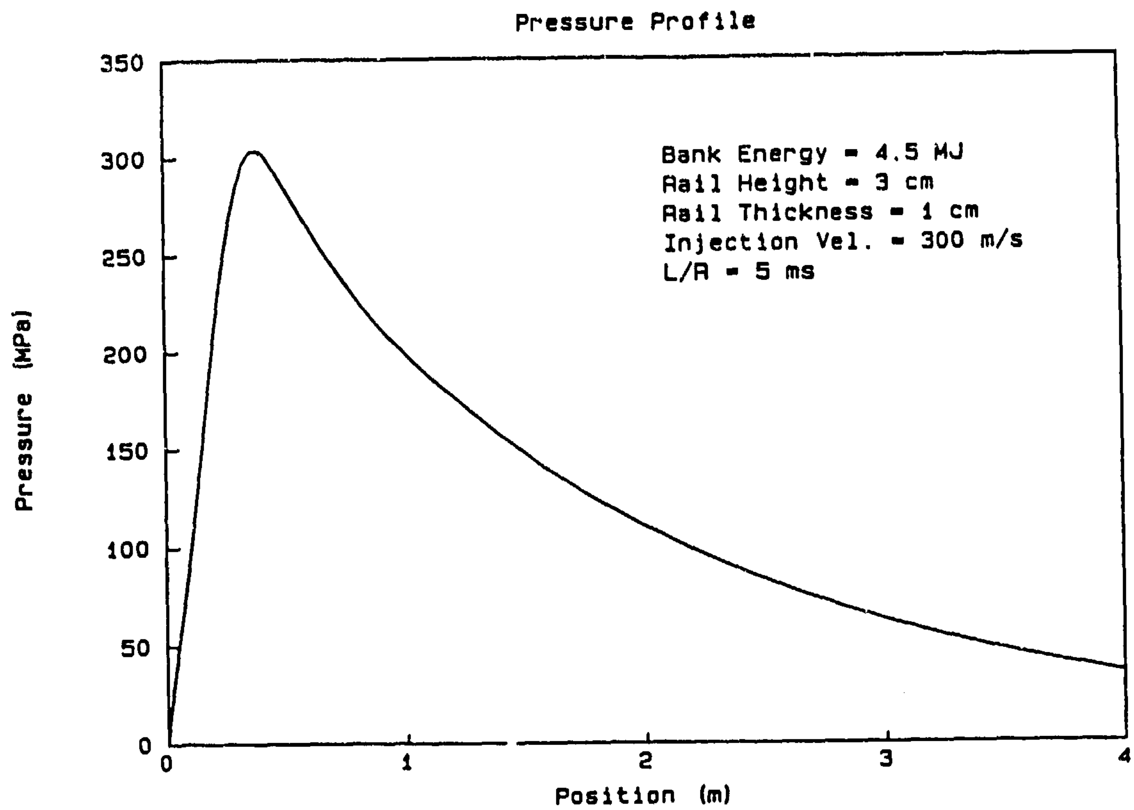

Figure 2.11. Baseline Design Pressure Profile

barrel length to establish the connecting stud spacing. This design request was made by the Contract Technical Monitor to keep additional design flexibility available should more effective switching circuitry becomes available during the course of operation of the proposed facility.

The projectile position and the corresponding rail resistance history are provided in Figures 2.12 and 2.13. The rail resistance takes into account the skin effect in the rails and the maximum value is approximately .9 milliohms.

A calculation was also provided to evaluate the same railgun configuration operating with only 1 MJ of capacitor bank energy. This may be the case if the power supply is purchased in increments. Operating at the lower bank energy and assuming a launch package mass of 65 gms, the pulse shaping inductor coil was re-optimized ($L = 7 \times 10^{-7}$ H) to maintain the same bore pressure (45 ksi) and L/R time constant of 5 ms. This optimization will maximize the final projectile velocity. The resulting system design gives an exit velocity of 1450 m/s, which is an increase of 30 percent over the same design without the inductor coil optimization.

These baseline design values were used in the development of the conceptual design which included the barrel cross-section selection, material selection, pre-load configuration, and stress analysis.

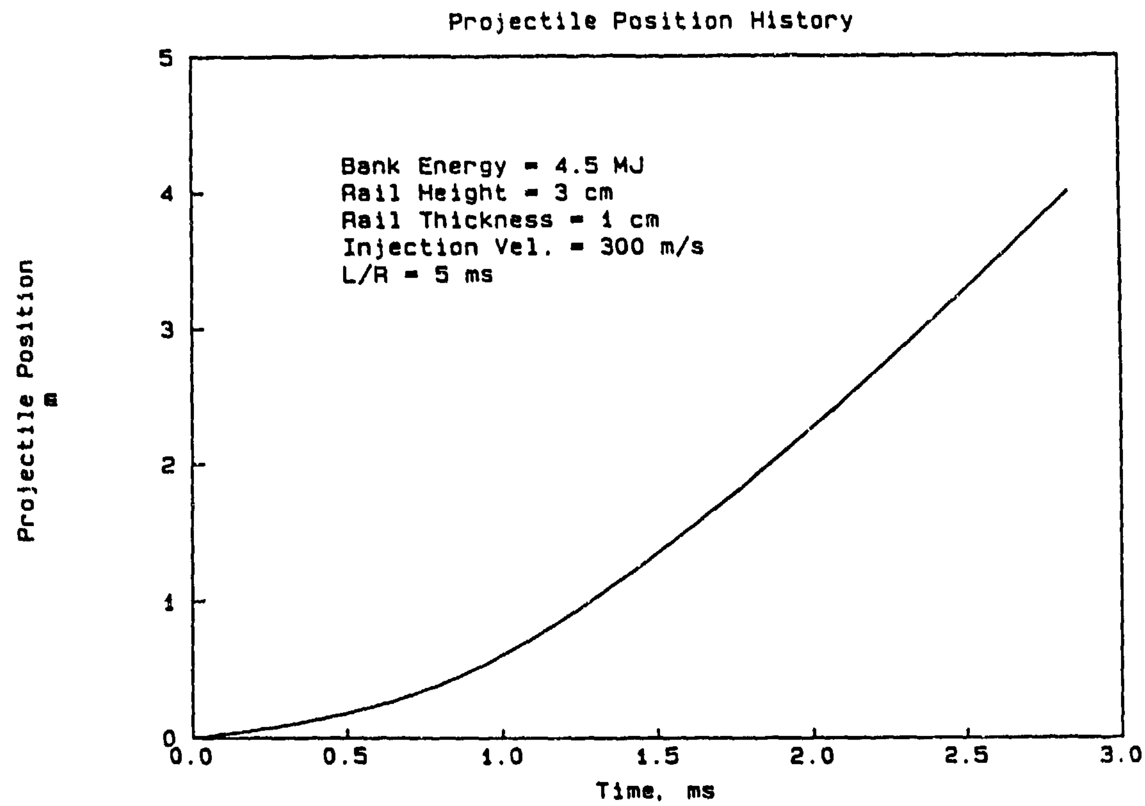

Figure 2.12. Baseline Design Projectile Position History

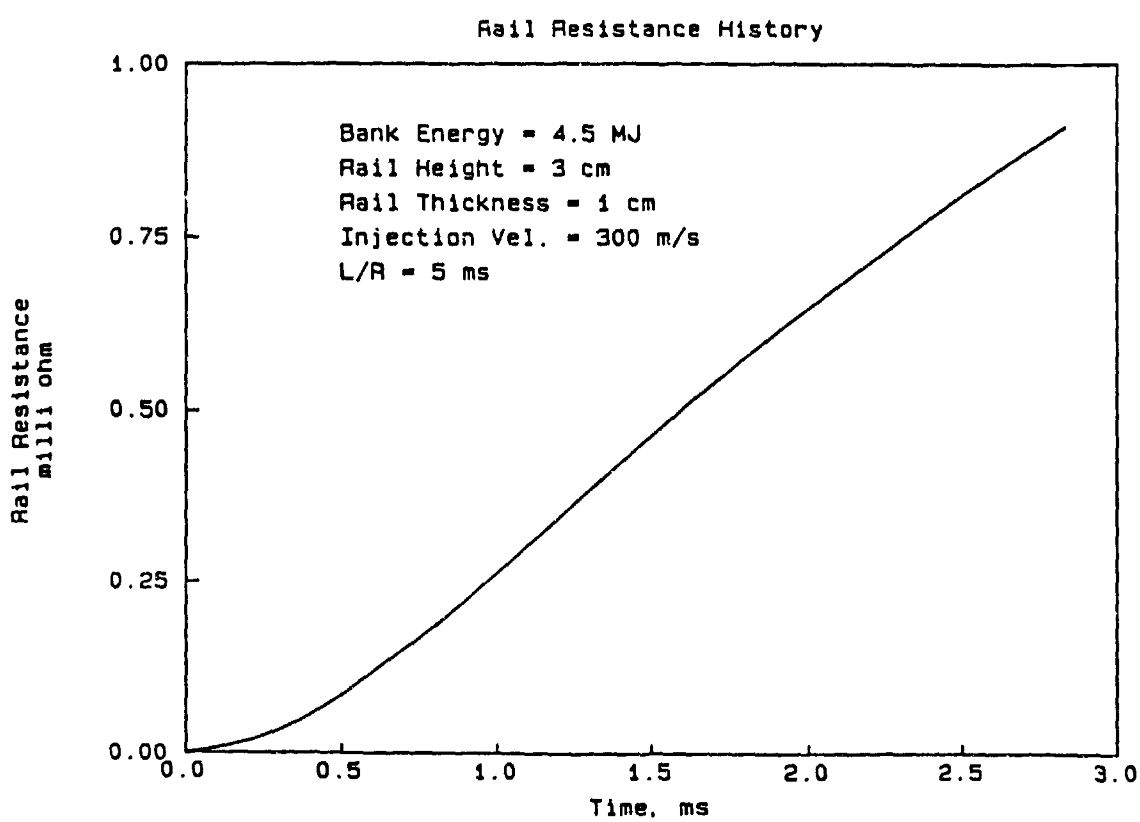

Figure 2.13. Baseline Design Rail Resistance History

3.0 CONCEPTUAL DESIGN

The selection of the baseline railgun parameters established the design basis for the conceptual design. The primary focus of the Phase I design study addressed the following conceptual design areas:

1. Selection of the overall barrel containment configuration and preload methods.
2. Selection of advanced materials for the rail, bore insulator, and backup insulation.
3. Evaluation of the effectiveness of preload transfer to the rail/bore insulator interface.
4. Stress and displacement analysis of the selected barrel cross-section configuration.
5. Development of the interface requirements (mechanical, electrical, pneumatic, and diagnostic).
6. Development of the conceptual arrangement of the railgun system with the support structure, maintenance and assembly equipment.
7. Estimate of the cost of the proposed railgun design.

The railgun design utilized a combination of innovative design features and the application of advanced, high performance materials. The central requirements for the design included the following:

- High utility (maximum shots per day)
- Easy and rapid maintainability and repair
- Easy upgradability
- Ready diagnostic access
- Multiple shot capability between tear-down/long life
- High reliability and structural integrity

Innovative design features provide ease of maintenance, repair, upgrade and diagnostic access. The capability for multiple shots between tear-downs as well as high reliability and structural integrity will result from the use of advanced materials and robust structural design concepts.

3.1 Barrel Containment Configuration

During a railgun shot, the barrel is subjected to intense transient electromagnetic, thermal and mechanical loads which tend to expand the railgun bore. The barrel bore must be compressively prestressed prior to railgun firing such that these transient loads do not cause gaps to open up at rail-insulator interfaces during firing. If gaps occur plasma losses and plasma blowby result which reduces system efficiency. Spallation damage may also occur in the insulators, induced by tensile waves resulting from dynamic gap closure after plasma passage.

Available approaches (bolted and single tube containment designs) for prestressing railgun bores, are compared in Table 3.1. The single tube containment system although effective for pressure confinement would require the preload force to be applied after the internal barrel components were slid into place. This would require an active pressurization system to apply the required preload and still allow disassembly of the internal bore components for replacement. The combination of sliding 4 meters of internal components into the circular containment tube on assembly or disassembly and the requirements of easy internal bore component replacement was considered extremely difficult for the one-man crew. The single tube containment system although

TABLE 3.1. Containment Options for Achieving Barrel Prestress

Description	Advantages	Disadvantages
<u>Bolted Design</u> Rectangular or Split Tube	o Proven in experiments o Relatively simple replacement of bore components o Adaptable to diagnostics o Very controlled preload	o Massive o Not weapon application o Eddy current losses
<u>Single Containment Tube</u>		
Prestressed Fiber Overwrap	o Relatively inexpensive o Isotropic prestress	o Limited prestress achievable due to fiber failure near bore o Difficult replacement of bore components (Overwrap destroyed) o Prestress level difficult to control
Cast Insulator in Prewrapped Composite Barrel	o Relatively inexpensive	o Insignificant prestress achievable due to relaxation of insulator during curing o Difficult/impossible to replace bore components o Prestress level difficult to control o Prestress no likely to last after first or second shot
Pressure Cured Epoxy Region Inside Jacket	o No active prestressing subsystem required o Some preload applied	o Relaxation/loss of prestress with some deformation o Difficult/impossible to disassemble bore components
Actively Pressurized Barrel	o High controlled preload o Preload maintainable for multiple shots o Relatively simple replacement of bore components o Compact/lightweight o Applicable to weapons	o Additional required subsystem (for pressurizing barrel) o High pressure seals required

preferable for a fielded weapon system, was therefore abandoned because more manpower is required to assemble and disassemble.

A split circular tube configuration was considered with the preload application by bolts. The preload application for the circular configuration and the rectangular strongback configuration are accomplished by essentially the same method. Therefore, the major advantage of one configuration over the other would be lower cost and simplicity in design. The use of advanced materials in the railgun design favored the rectangular cross-section since current material fabrication (i.e., for advanced ceramics) is in small rectangular pieces. Transitioning from the rectangular shapes to the outer curved sections would require additional machining or grinding and is not as effective from a material use standpoint.

The technique most suited to the requirement in this program was the bolted rectangular design wherein the rails, insulator and backing materials are encased in a bolted steel jacket. Examples of bolted designs are shown in Figure 3.1[1-3]. The rectangular bolted design has the advantages of being well developed (currently in use in both CHECMATE and HYVEL), and it lends itself to relatively simple assembly and, bore component replacement. The bolted design is cost effective based on currently available sizes and shapes of the advanced materials utilized. The bolted design makes very efficient use of laboratory space because a bottom-up assembly procedure can be used and the need to slide barrel-length components in and out of barrels is obviated. Disassembly and reassembly can be performed easily and rapidly by one man using a stud tensioner and overhead crane. Rails, insulators, high pressure seals, diagnostic probes and backing materials can all be readily examined, refurbished or replaced once the jacket has been unbolted and the top removed.

The barrel steel containment structure and the interior components are designed for fabrication in 1 meter sections such that only portions of the barrel need be disassembled. This feature may prove advantageous since it is anticipated that the barrel breech end, where plasma moves slowest, will experience the highest bore erosion. For high utility operation (up to five shots per day) the bore could be conditioned between shots by using a honing tool to remove soot build-up. The use of refractory metals and ceramics at the bore surface will minimize erosion/melting.

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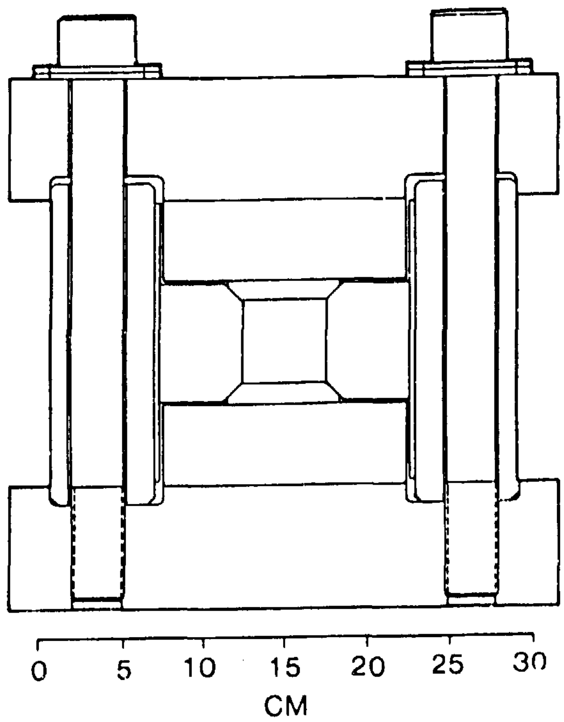
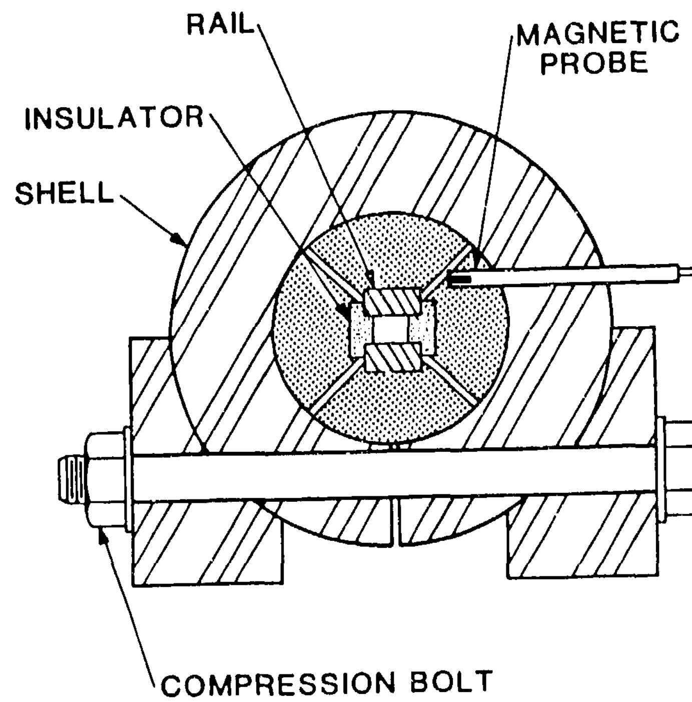
1 Parker, J. V., and W. M. Parsons, "Experimental Measurement of Ablation Effects in Plasma Armature Railguns," Proceedings of 3rd Symposium of EML Technology, Austin, Texas, 1986, pp. 181-188.

2 Simo, J. R., K. E. Christensen, C. E. Cumings, and N. C. Calkins, "A Launcher Barrel for the Lethality Test System Rail Gun", Proceedings of 3rd Symposium of EML Technology, Austin, Texas, 1986, pp. 281-284.

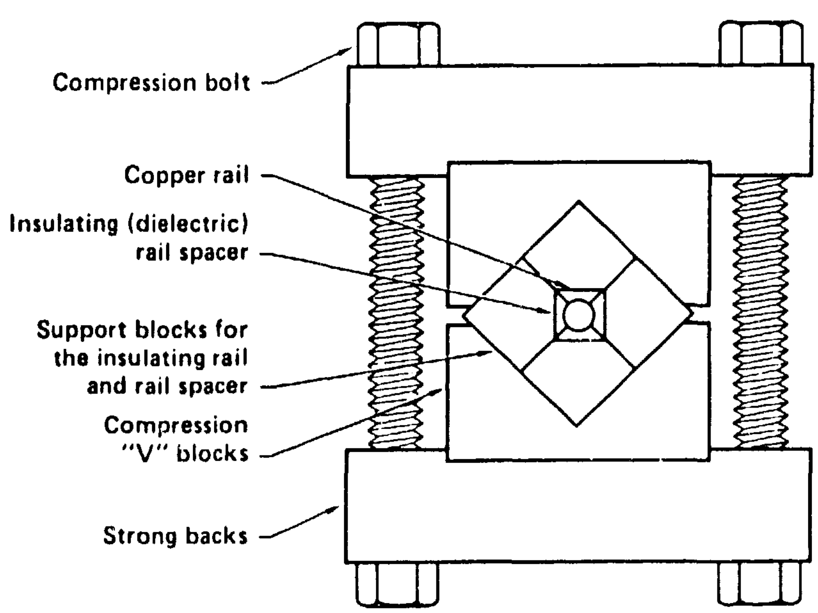
3 Holland, M. M., G. M. Wilkinson, A. P. Krickuhn, and R. Dethlefsen, "Six Megajoule Rail Gun Test Facility," Proceedings of 3rd Symposium of EML Technology, Austin, Texas, 1986, pp. 97-102.



CHECMATE Railgun at Maxwell Labs



MIDI-2 Railgun at LLNL



Railgun at LLNL

Figure 3.1 Examples of Bolted Railgun Designs

3.2 Structural Design Features

The conceptual design began with a preliminary structural analysis of a configuration similar to the selected design. Two possible design improvements were identified. These included relocating the applied preload and using higher strength/higher stiffness advanced materials for the bore components. The exploitation of the improved properties of the advanced ceramics for both the insulator and the backup insulator showed a significant reduction in the calculated deflections. This combined with relocating the preload resulted in a very efficient structural containment that transmitted the preload directly to the critical bore rail/insulator interface. The resulting conceptual design shown (see Figure 1.2) relies on maintaining a compression seal to the plasma at all times along the bore rail/insulator interface. Backup high pressure seals are provided only as a redundant system. High compressive strength materials are desirable. Such materials tend to be less ductile and more flaw sensitive than weaker materials. However since the materials are always in a state of compressive confinement, lack of ductility and high flaw sensitivity (low fracture toughness) become somewhat less critical. Thus, high strength materials will produce a high safety margin barrel and the ductility and flaw sensitivity concerns which exist primarily at stress concentrations can be addressed through established design practice for brittle materials.

High material stiffness increases barrel efficiency, where efficiency is taken as change in projectile kinetic energy as a percent of plasma work. High stiffness barrels experience less bore distortion during both preload and firing relative to low stiffness barrels. Lower distortion causes less projectile pinching, plasma blowby and projectile jitter all of which absorb plasma energy. Further, bore dimensional tolerances are easier to maintain. Our design approach was to use materials in the barrel that had both high stiffness and high strength.

The railgun barrel components shown previously in Figure 1.2 are simple structural shapes which minimize fabrication costs. Overall design efficiently transfers the stud preload directly to the rail/insulator interface without unnecessary loading of surrounding material. The top and bottom strong back plates together with the side walls constitute the containment structure. Insulating backing material electrically isolates the rails from the steel containment. The four high pressure seals, traverse the entire length of the barrel and serve as redundant backup seals. The preload applied by tensioning the Grade-8 studs, is transferred from the strongback plates to the backup insulators and then into the rails. Appropriate parts tolerancing will ensure the proper load transfer to rails and insulators and will minimize the vertical load to the side walls and high pressure seal region. Rail loads are transferred into the insulator across the 45^{o} rail/insulator contact surfaces. The insulators are supported by backing insulator blocks which are supported by the containment side walls. Finally, the sidewalls are restrained against lateral motion through contact with the strongback plates. The contact areas between plates and side wall will be the minimum necessary to provide adequate support for containment. A large contact area is undesirable since the stud loads may be partially supported by the sidewalls through shear transfer.

Table 3.2 provides a summary of the salient design features specifically developed for the BRL railgun design study.

TABLE 3.2. BRL Utility Railgun Design Features

Advanced Materials

Rail Conductor	Mo Clad Cu - Al_2O_3
Bore Insulator	Si_3N_4
Backup Insulator	SiAlON

Location of Applied Preload Optimized

- o Transmits the stud tension preload to the region directly above the bore rail/insulator interface

Stud Tensioner to Apply Preload

- o A more accurate method of application
- o Less damage to backup washer

3.3 Conceptual Design Analyses

A series of stress analyses were performed on the conceptual design.

The objectives of these analyses were to:

1) Refine definition of the load transfer path between the steel strong-back plates and the rail-insulator interfaces.

2) Assist in the selection of materials for bore and backing insulators.

Analysis Geometry

For the conceptual design phase, two dimensional, static, elastic, plane strain stress analyses were performed using an IBM PC-AT version of the NISA(4) finite element code. The analysis geometry is shown in Figure 3.2. The steel containment structure was not modeled; instead its affects were simulated through the boundary conditions. The analysis geometry represents one quadrant of the rail-insulator-backing configuration. Figure 3.2 also shows the finite element mesh which consisted of twenty 8-node isoparametric plane strain elements. It was assumed that a gap existed between the two blocks of backing insulation and that the gap did not close under load. Interfaces between the rails and insulator, rail and backing, and insulator and backing were assumed to have sufficient friction that no slipping occurred when loads were applied.

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[4]NISA II Finite Element Analysis Program available from Engineering Mechanics Research Corporation, Troy, Michigan

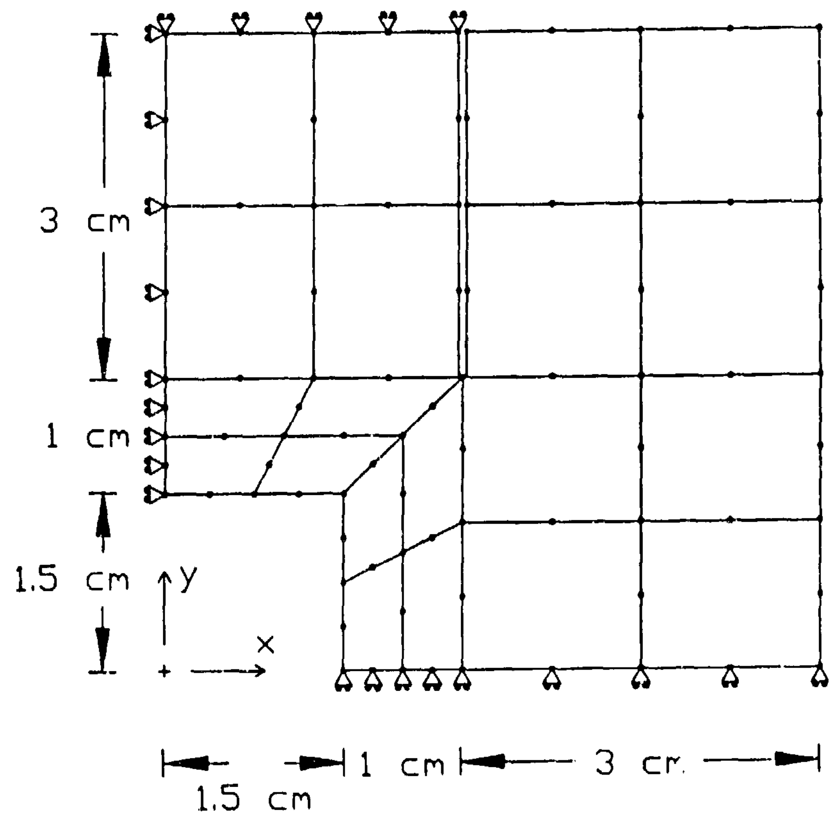


Figure 3.2. Analysis Geometry with Superposed Finite Element Analysis Mesh

Material Properties

The material properties used as input for the analyses are discussed in Section 3.4. Only the elastic modulus and Poisson's ratio were used since analyses were entirely elastic. The strength properties were compared to stress results to determine margins of safety. In the analysis, a very stiff design was compared to a relatively soft design. The stiff design assumed Si_3N_4 bore insulators and SiAlON backing insulators while the softer design used G-10 for both backing and bore insulators. Composite material G-10 has seen extensive use in the railgun community and served as a baseline material against which to compare the stiffer materials. The rail material was taken to be Al-60.

Applied Loads

Preload from torquing the Grade-8 studs was simulated by applying uniform pressure along portions of the rail backing-material out edge. The total preload was 4.65 MN and was applied in three different distributions, as shown in Figure 3.3.

Electromechanical loading from plasma pressure and rail material repulsive forces was simulated as a uniform 310 MPa (45 ksi) pressure applied to both the rail and insulator bore surfaces.

Analysis Results

Two analysis series were performed. The first series objective was to determine the most effective preload placement and the second series objecresults given here are preliminary since only a simple finite element model was used, however the trades and qualitative comparisons are valid.

Preload Placement

All results for the preload placement study are for the stiff barrel design where the bore and backing insulators are taken as Si_3N_4 and SiAlON respectively. Figure 3.4 shows backing insulator deflections directly beneath the applied preload for each of those preload placements. Preload I caused high tensile stresses in the backing insulation (approximately 80% of material tensile strength) at location X in Figure 3.4. Also tensile stresses were predicted at location Y, Figure 3.4 which implies that under preload the bore insulator and backing insulator separate at Y. This is very undesirable because the bore insulator would then impact the backing insulator during plasma loading. Preload II, which is a weighted linear combination of preloads I and II also induced some tension at location X.

Table 3.3 gives the normal stress across the 45^0 rail-insulator interface at the bore. While the precise values are probably not accurate, compressive stress at the bore increases as the preload moves to directly over the bore. Thus for the same total force, preload III induces higher bore compression than preload I, thereby reducing the possibility of plasma blowby and dynamic rail-bore insulator gap closure.

TABLE 3.3 Normal Stress (Compressive) Across Rail/Insulator Interface at Bore as a Function of Preload for Stiff Design

Preload	Normal Stress (MPa)
I	234
II	240
III	248

Table 3.4 gives the maximum bore deflection as a function of preload. As was expected, preload III induced (58%) more deflection more than preload I. However, all bore deflections are small (<0.0014 in).

TABLE 3.4. Maximum Bore Deflection as a Function of Preload for the Stiff Design

Preload	Maximum Deflection (10^{-5}m)
I	2.14
II	2.70
III	3.38

It was concluded that preload III is preferable because no tensile stresses were predicted in the backing insulator; no gaps opened up between the bore and backing insulators; and the highest level of bore compressive stress was achieved.

In the Phase II program, preload placement will be further refined to more directly load the 45^0 rail/bore-insulator interface and reduce tensile stresses in the rail.

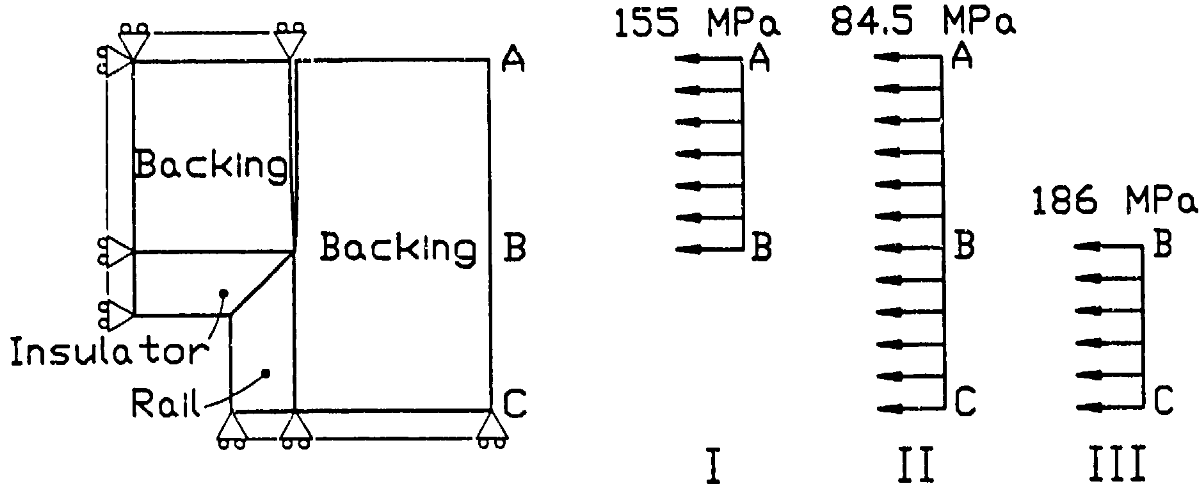


Figure 3.3. Barrel Preload Intensity and Placement

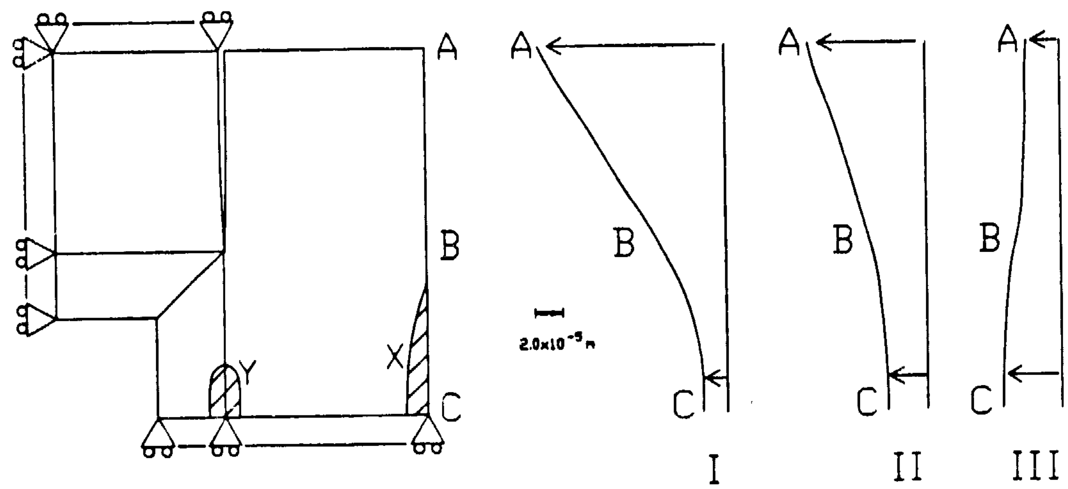


Figure 3.4. Deflection of Backing Insulator Along Edge ABC
as a Function of Preload I, II, and III

Soft Vs. Stiff Bore Design

G-10 is a resin matrix composite with orthogonal reinforcement. The chosen reinforcement directions corresponded to those used in CHECMATE as shown in Figure 3.5. Results reported here are for preload III only, both with and without plasma pressure active.

Under preload III the G-10 design experienced 1.62×10^{-4}m maximum inward bore motion at node 1; a factor of 4.8 times larger than with the stiff design. Maximum tensile stress in the rail was predicted to be 675 MPa or 11% over the uniaxial tensile strength of the Glidcop Al-60. For the stiff design, maximum rail tensile stress was 43 MPa.

Figure 3.6 compares bore expansion at several locations for the soft and stiff designs under simultaneous action of plasma and preload. The maximum bore deflection of the soft design is 66 times that for the stiff design. Also bore distortion for G-10 is highly non-uniform so that the bore does not even remain rectangular. The combination of large bore displacement and large bore distortion implies that plasma blowby may occur which will degrade system efficiency. Also optimum projectile geometric design will be complicated.

Based on the proceeding discussion, a stiff bore construction is preferable because it produces less bore distortion during preload; less opportunity for plasma blowby and projectile pinching; and lower stresses in the Al-60 rails.

3.4 Material Selection

The selection of suitable bore materials is extremely important for achieving the concurrent goals of high utility, low maintenance and high performance. The baseline bore materials for the proposed launcher, including conductive rails, insulator spacer and backup insulator were selected based on the structural analysis of Section 3.3, an evaluation of the other materials requirements, the existing materials that might meet these requirements, available railgun data, an assessment of materials availability in the required size, and cost. A discussion of the materials selection rationale for each component is given below.

Conductor Rail

The key material requirements for the rail are:

- o Sufficient strength to withstand the maximum gun pressure of 310 MPa (45 ksi) and similar bending stresses from E-M repulsion forces without significant plastic deformation. A minimum yield strength of 345 MPa (50 ksi) was identified as a requirement.

- o Reasonably high electrical conductivity to prevent excessive rail ohmic energy losses and bulk heating. Although this is not as important for a single shot gun as for a repetitively fired one, a minimum conductivity of at least 50% of pure copper (3.46 micro-ohm cm) is considered desirable.

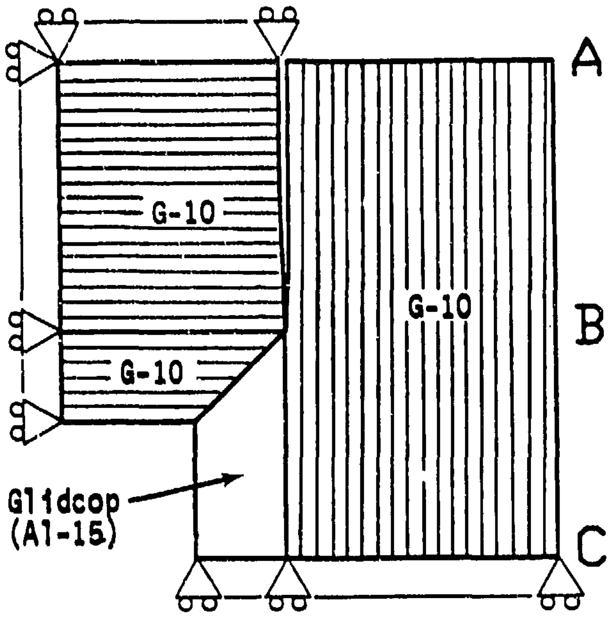
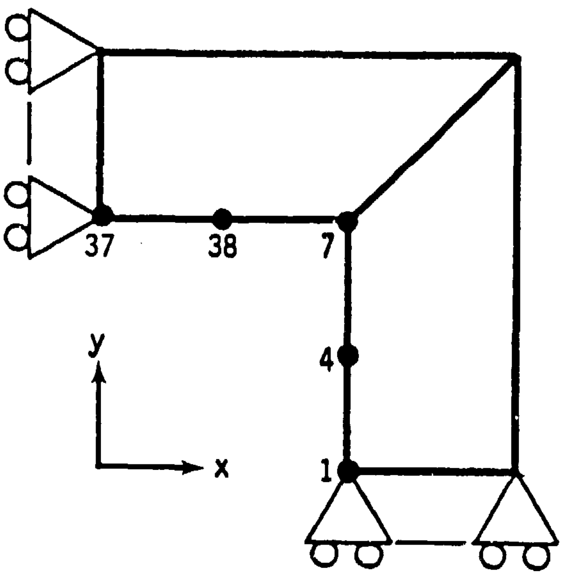


Figure 3.5. Soft Barrel Showing Orientation of G-10 Bore and Backing Insulators



Bore Displacement (10^{-5} m)		
dof*	Stiff Design	Soft Design
37y	2.85	190
38y	2.65	157
7y	0.41	4
7x	1.00	- 5.7
4x	2.55	- 1.3
1x	2.74	0.6

*dof = degree of freedom

(37y = node 37, y displacement component)

Figure 3.6. Displacement Comparison when Barrel is Under Simultaneous Preload and Plasma Pressure

- Erosion Resistance

  The rail surface must be capable of resisting material loss or transfer caused by ablation, melting or mechanical erosion. This is caused by both the interaction of the surface with the radiating plasma and ohmic heating due to surface currents. For the proposed design, the radiated plasma powers will be about 0.7 to 1.4 MW/cm^2. Material loss or transfer degrades performance by adding mass to the plasma, causing secondary arc restrike, and most importantly for a low maintenance gun, changing bore dimensions which might cause blowby or projectile interference.

In order to best meet both the bulk and surface rail materials requirements, a bimetallic, refractory metal clad rail was selected. This concept was developed in a previous program[5] and is based on SPARTA's unique low temperature solid state bonding process for joining refractory metals to copper alloys. The high temperature refractory cladding of 0.5 to 1 mm (0.020 to 0.040 inches) provides melting and erosion resistance at the surface while the higher conductivity copper alloy bulk conductor minimizes ohmic dissipation.

High strength, high conductivity Cu-Al_2O_3 dispersion strengthened alloy (Al60) was selected as the baseline rail bulk conductor material. Several candidate copper alloys with conductivities above 50% I.A.C.S. were evaluated as shown in Table 3.5. The 0.6 wt % Al_2O_3 alloy was selected because it had the strength (83 ksi) to survive the maximum pressure and E-M loads and very high conductivity of 80% I.A.C.S. Most importantly its mechanical properties are not degraded after rail heating, which should assure long lifetime.

The refractory metal cladding alternatives have been evaluated previously[5] and the results are shown in Table 3.6 and Figure 3.7. Tungsten, molybdenum, tantalum-10% tungsten, and tantalum solid-state bonded claddings were evaluated along with detonation gun sprayed tungsten carbide-10% cobalt and commercially pure bare copper. Tungsten showed a factor of four decrease in melt depth compared to copper, 60% better performance than molybdenum. Tungsten was selected as the baseline cladding material, with molybdenum which is significantly more fabricable, as the backup. The cladding will be applied in a thickness of 1 mm (0.040 inches). This thickness permits the bondline to remain sufficiently cool (near ambient temperature) during the shot and allows adequate current penetration to the bulk conductor.

<u>Insulators</u>

The insulator components include the bore insulator which separates the rails and faces the bore environment, and the backup insulator segments that transfer load from the bore components to the structural support. Some of the material property requirements for the two components are similar, others differ. These are summarized below.

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[5] S. N. Rosenwasser and R. D. Stevenson, "Development of Erosion Resistance Rails for Multishot Electromagnetic Launchers, AFATL-TR-86-34, May 1986.

TABLE 3.5. Room Temperature Properties of Candidate Rail Substrate Materials

Alloy Desig.	Comp. Wt. %	YS MPa (ksi)	UTS MPa (ksi)	e %	E GPa (Msi)	K_T W/m-K	K_e* % I.A.C.S.
OFHC Cu (C10100) 40% CW	99.96 Cu	323 (47)	345 (5G)	12	119.3 (17.3)	394	101
CuZr (C15100) 70% CW	Cu-0.15 Zr	411 (60)	427 (62)	16	129.0 (18.7)	380	90
Glidcop Al-15 (C15715) 20% CW	Cu-015 Al_2O_3	434 (63)	455 (66)	21	113 (16.4)	365	92
Glidcop Al-60 (C15760) 40% CW	Cu-0.6 Al_2O_3	572 (83)	607 (88)	11	137.2 (19.9)	322	80
CuNiBe (C17510) HT Condition 40% CW	Cu-2.0 Ni-0.4 Be	814 (118)	931 (135)	15.9	135.8 (19.7)	249	63
CuCrZr (C18100) 75% CW	Cu-0.8 Cr-0.14 Zr	514 (75)	538 (78)	13	125.5 (18.2)	320	82
CuCr (C18200) 40% CW	Cu-0.9 Cr	407 (59)	462 (67)	14	117.2 (17.0)	330	81

* 100% I.A.C.S. = 1.7241×10^{-8} ohm-m

TABLE 3.6. Maximum Melt Depths for Conductor Rails

Relative Cladding Material	I = 160 kA, V ~200 BRL Gun	I = 290 kA, V ~175 PUG Gun	Arc Melting Resistance*
Tungsten	1.0	-	6.14
Molybdenum	2.5	4.0	4.26
Tantalum-10% Tungsten	-	2.8	3.17
Tantalum	2.9	-	3.29
WC-13% Co	1.4	2.7	1.20
Cu-110 (Unclad)	4.0	7.0	3.52

* x 10^9 W/m^2 at 300^{o}C

- o High elastic modulus is the key requirement for the backup insulators as discussed earlier in Section 3.3. A modulus of at least 206 GPA (30 Msi) is required for acceptable bore deformations. High compressive strength (at least 414 MPa [60 ksi]) is also important along with reasonable fracture toughness (at least 4 MPa-$m^{0.5}$). Ablation erosion resistance is not a requirement for the backup insulator which is not exposed to the plasma.

- o Ablation/erosion resistance is the key requirement for the bore insulator. Adequate compressive strength >414 MPa (>60 ksi), high flexural strength >482 MPa (>70 ksi) and reasonable fracture toughness (4.0 MPa-$m^{0.5}$) are also required to resist failure from the dynamic bore mechanical loads, particularly at stress concentrations.

Based on these property requirements, ceramics were the obvious choice for both the bore insulators and the backup insulator as discussed in detail in Section 3.3. Fine grained advanced ceramics offer significantly higher thermal resistance, elastic modulus, and strength than the more common unreinforced or fiber reinforced polymers, glass composites or conventional technical ceramics as shown in Table 3.7.

High purity silicon nitride (Si_3N_4) was selected as the baseline bore insulator material because it demonstrated the best ablation/erosion resistance and thermal shock resistance relative to other ceramics or polymer based insulators in previous railgun tests at BRL[6]. The measured depth of ablation/melting after BRL railgun testing are shown in Figure 3.8.

The compressive strength (3.2 GPa [464 ksi]), elastic modulus (330 GPa [48 Msi]), and fracture toughness of Si_3N_4 are excellent. However, fracture resistance at the high dynamic loadings projected for the proposed gun must be verified. These materials tests will be performed in the next several months at BRL, with Si_3N_4 and new toughened ceramic composites. Glass reinforced polyimide is an alternative for the Si_3N_4 or other ceramic but survivability has to be demonstrated. The use of the polyimide would cause significantly more ablation, its lower strength would require increased bore size (lower pressure), and bore deflections would be significantly increased as discussed previously.

The Si_3N_4 would be procured from Cercom, Inc. in Vista, California. Cercom supplied General Electric with over 500 pounds of their high purity grade of Si_3N_4 for use in the advanced barrel studies. In addition, ball bearing wear tests have proved the material to be of very high quality, and superior in erosion resistance to several other grades of Si_3N_4 and SiC.

The backup insulator will be SiAlON, a lower temperature very high compressive strength, (3.74 GPa [543 ksi]), high modulus (305 GPa [44 Msi]) moderate toughness ceramic that can be supplied in large pieces and is reasonably inexpensive. Again, the use of glass reinforced insulator (G10 or G11) would necessitate a lower pressure, lower performance barrel.

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[6] S. N. Rosenwasser and R. D. Stevenson, "Selection and Evaluation of Insulator Materials for High Performance Railgun Bores," IEEE Trans. Magn. Vol. MAG-22, November 1986, pp. 1722-1729.

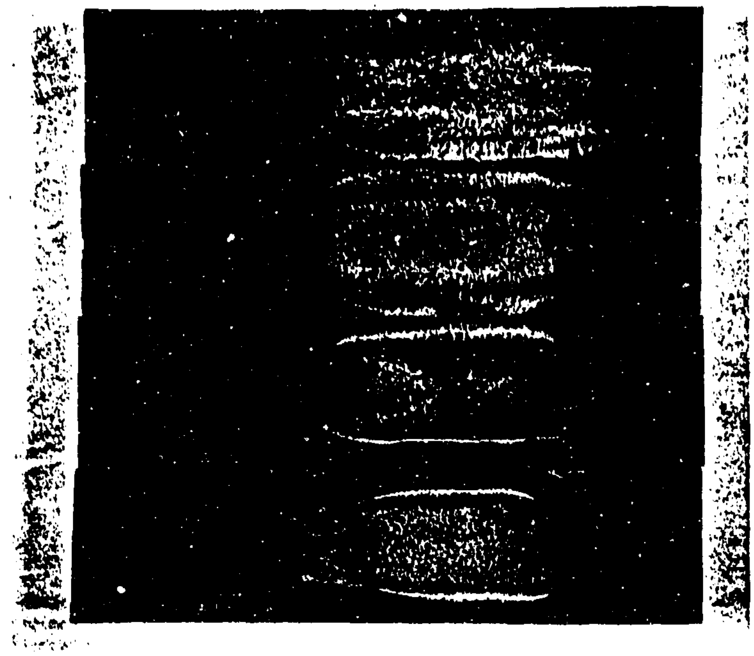

Figure 3.7. Surface of Unclad Copper 110, and 0.25 mm Tantalum, Molybdenum (Mo), and Tungsten (W) Clad to Copper Rails (top to bottom) Tested in BRL Railgun. Melt Depths of W and Mo were about 1/4 and 1/2 that of Cu, respectively.

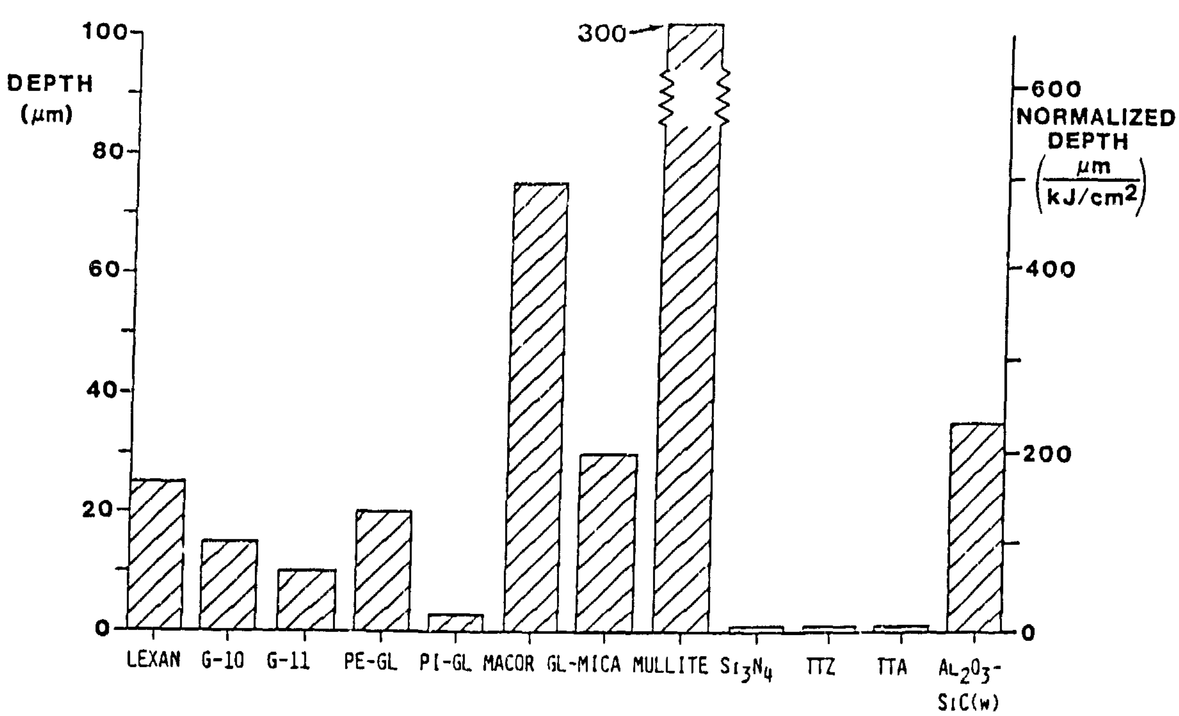

Figure 3.8. Depth of Ablation/Melting on BRL Railgun Tested Insulators

TABLE 3.7. Room Temperature Properties of Insulating Rail Materials

	MOR/ σ_{UTS}	σ_C	E	K_{IC}	Density	CTE ($\times 10^{-6}$)	K_T	ρ_e	C_p	T
	MPa	Mpa	GPA	MPa-$m^{0.5}$	kg/m^3 ($\times 10^3$)	at RT (m/m/K)	W/m-K	ohm-m	J/kg-K	^oC
Organic Polymers										
Lexan[a]	93	86	2.4	-	1.20	80.0	0.3	$>10^{14}$	1200	390
Glass Fiber Re-inforced Polymers										
G-10 CR	415[b]	420[c]	14.0[c]	-	1.90	10.5	0.73	9.3×10^{12}	1570	170
G-11 CR	470[b]	461[c]	15.9[c]	-	1.95	10.0	0.68	1.3×10^{13}	1570	190
Polyester Glass	240[b]	410[c]	13.1[b]	-	1.7	-	-	-	1570	240
Glass Polyimide	552[b]	520[c]	20.7[b]	-	2.20	8.0	-	5×10^{13}	-	320
Inorganic Glass Composites										
Macor[d]	103	345	65.5	-	2.52	9.4	1.3	$>10^{12}$	757	1100
MM-1100[e]	83	221	73	-	2.8	9.4	5.9	$>10^{12}$	460	625
MM-400[e]	103	310	76	-	3.0	10.5	4.2	$>10^{10}$	502	400
Conventional Technical Ceramics										
99.9% Al_2O_3O	552	3792	386	2.5	3.96	6.4	39.0	$>10^{13}$	880	2000
Mullite	31	320	155	2.2	2.3	3.7	4.1	$>10^{11}$	848	1850
Advanced Ceramics										
SiC (Sintered)	462	3861	406	4.6	3.10	4.02	126	.002 to 3.0	669	2500
Si_3N_4 (Sintered)	655	2758	276	5.0	3.28	2.6	27.6	$>10^{13}$	810	1900
PSZ	634	2000	205	10.0	5.70	8.6	2.2	$>10^{9}$	400	2764
AlN (Hot Pressed)	621	2068	345	4.0	3.20	5.6	34.0	$>10^{12}$	700	1990
Sialon	745	3747	304	6.5	3.26	2.0	11.9	$>10^{11}$	712	-
Reinforced Ceramics										
Al_2O_3-SiC(w)	641	4250	393	8.0	3.74	6.0	33.0	7	825	2040

[a]General Electric Corporation
[b]Warp/Fill Direction
[c]Normal Direction
[d]Corning Corporation
[d]Spaulding Fibre Corporation

SiAlON has been used by Los Alamos National Laboratory as a backup insulator in their prototype LTS railgun. This six foot long gun has successfully fired numerous 2 MJ shots without any fracture of the SiAlON. In addition, the use of the SiAlON resulted in a very small rail deformation of 75 to 100 microns (0.003 to 0.004 inches) compared to ten times this large using G-10 backing.

3.5 Overall Design Description

The conceptual design drawings of the railgun are provided in Drawings BRL-01,-02,-03 and are included in the Appendix. These drawings conceptually address the design of the strongback, (sizing, stud spacing), support structure, bore component segmentation, interface to the gas injector, electrical leads, diagnostics, stud tensioning, and overhead crane requirements. Figure 1.3 illustrated an isometric of the proposed railgun. The railgun is designed to minimize the number of people required to assemble, maintain and operate the railgun. Attention was given to the physical sizing of the railgun subcomponents for ease of handling. The weight of the largest subcomponent (bottom strongback plate) is approximately 680 kg (1500 lbs.). Lifting lugs are provided on all the large subcomponent pieces. The over head crane allows both vertical and axial movement. Transverse movement is accomplished by moving the crane support frame which has rollers and rests on a track. The transverse motion can be either manual or hydraulically driven.

The overhead crane provides full access to the railgun components (i.e., barrel segment, strongback containment, fast acting valve, light gas injector). The components can be lifted and positioned to a designated floor area for component layout. As the facility requirements become better defined the overhead crane may be modified to include the overhead support track in the building structure. For this design study, however, we assumed a complete stand-alone structure.

Stud Tensioning

Traditional bolt and stud tightening methods are inefficient, since most of the force required to tension a stud is wasted in overcoming friction between the threads and between the nut and restrained member. Damage at the friction surfaces often occur. In addition, accurate loading is difficult because applied torque is measured not the resulting bolt preload. To overcome these problems a hydraulic stud tensioner is utilized to preload the large (1-1/4 inch diameter) studs quickly, accurately and safely. Hydraulic force is used to stretch the stud rather than to torque the bolt to the required load. The system consists of a compact jacking tool that hydraulically stretches the stud and spins down the closure shut. This system is shown in the railgun isometric drawing. The preload can be accomplished by one man. A predetermined sequence of loading on the top strongback closure plate will minimize any flange distortion. In addition, multiple stud tensioners, tied to the same hydraulic source could be used to simultaneously tension several bolts and reduce the assembly time. Quick disconnect couplings and flexible hose make the system quick and convenient to use.

Projectile/Arc Injection

The projectile injection velocities ranging from 200 to 500 m/s are obtainable from a single stage gas gun, operated by a fast acting valve. The alternative option is to use a burst disk which has been utilized in Maxwell's railgun facilities. The burst disk helium injector can attain injection velocities of 800-1000 m/s. The priority in this study however, was given to ease of operation and high utility rather than higher injection velocities.

A 2 liter helium gas vessel operating at 2500 psi is shown coupled to the 1 1/4 inch fast acting valve. The valve fully opens in less than 1 ms. The valve is connected by a flange coupling to the 1.5 m pre-accelerator barrel. Each of these components rests on a roller bearing assembly connected to the support structure. This allows each of the components to be disconnected and slid back for access during assembly, maintenance and/or projectile loading. The pre-accelerator barrel is also connected to the railgun breech by a bolted flange.

Electrical Connection

The electrical leads interface with the breech end of the railgun. The connecting buswork would enter from the bottom and would be bolted to the current collector plates at six locations. The details of the connector plates would be developed during the Phase II detailed design. Their design would follow the current design practice used at Maxwell's facility.

Diagnostics

Provision is made to supply diagnostic channels at 10 cm center-to-center spacing for the first 1 meter barrel segment. The remaining 3 meters will use a spacing of 40 cm. The diagnostic hole size is 1.25 cm (.5 inch) diameter. A total of 17 diagnostic channels are provided, of which 10 are located in the first 1 m segment, and 7 in the remaining 3 m sections.

4.0 COST ESTIMATE

The preliminary cost estimate for engineering, design and hardware fabrication of the 3 cm square bore, 4 m long railgun support structure, injector system and crane is $499 K. Table 4.1 provides a breakdown of the cost elements. These costs are exclusive from any facility related costs associated with the power supply, diagnostics, and data acquisition, as well as any performance and acceptance testing.

TABLE 4.1 BRL Utility Railgun Cost Estimate

Engineering and Design Labor	Hrs.	$
Engineering Analysis	1400	80,000
Mechanical Design	2585	135,000
Materials and Fabrication		284,000
	3985 hrs.	$499,000

Maxwell estimates that the 4.5 MJ capacitor power supply will cost on the order of $1.5M. This includes the capacitor banks, controls, closing switch, and crow bar switch. It does not include the inductor and bus bars.

5.0 ROADMAP FOR DETAILED DESIGN, FABRICATION AND TESTING

The roadmap of the necessary tasks to complete the detailed systems analysis, design, fabrication/assembly and testing of the railgun is shown in Figure 5.1.

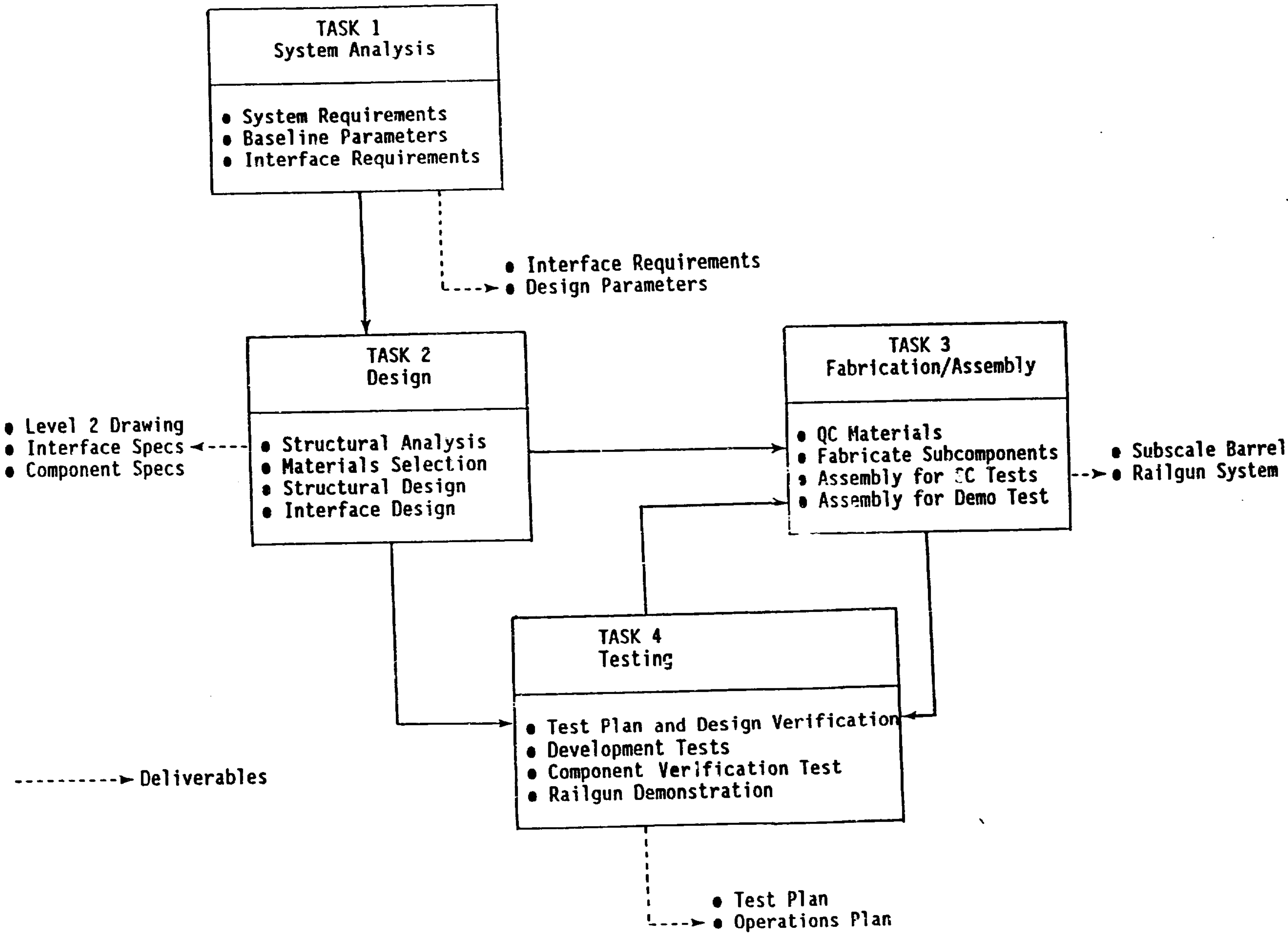

Figure 5.1 Roadmap for Final Design, Fabrication and Testing of BRL High Utility Railgun.

The comprehensive testing program is particularly important because of the performance and survivability of the advanced materials utilized must be verified prior to final commitment to fabrication of the full scale gun. A comprehensive testing program, starting early in the program is required and should consist of:

- o Development and Design Verification
- o Subscale Components Assembly Tests
- o Railgun Performance Validation
- o BRL Demonstration Tests

Development and Design Verification Tests

A testing program will be required for the barrel because of the utilization of advanced composite materials. Tests will include validating material erosion and structural performance in a small railgun such as HYVEL at pressures of interest. This is particularly critical to establish ceramic survivability.

Subscale Component Assembly Tests

A 1 m section (full size) of the barrel should be built including all the design features to demonstrate fabrication feasibility and develop tooling and assembly procedures prior to initiation of the 4 m barrel fabrication. The barrel should be tested at design current (1.2 MA) for several shots (not repetitive) at the CHECMATE facility to validate structural performance.

The barrel segment instrumentation requirements include B dot loops to determine rail current, thermocouples to determine peak temperatures and fast response strain gages to determine structural response. It is anticipated that portions of the 1 m barrel will be available as replacement parts for the 4 m barrel.

Railgun Performance Validation

The completed railgun assembly should be tested at CHECMATE. Suitable diagnostics to measure structural response will be used in addition to the usual railgun diagnostics.

BRL Demonstration Tests

After successful testing at the CHECMATE facility, it is anticipated that the railgun will be shipped and assembled at BRL. Demonstration tests, according to an agreed upon test plan should be performed with contractor personnel in attendance. It is envisioned that this will be achieved over a period of one (1) month, culminating in the demonstration of 5 shots/day utility factor.

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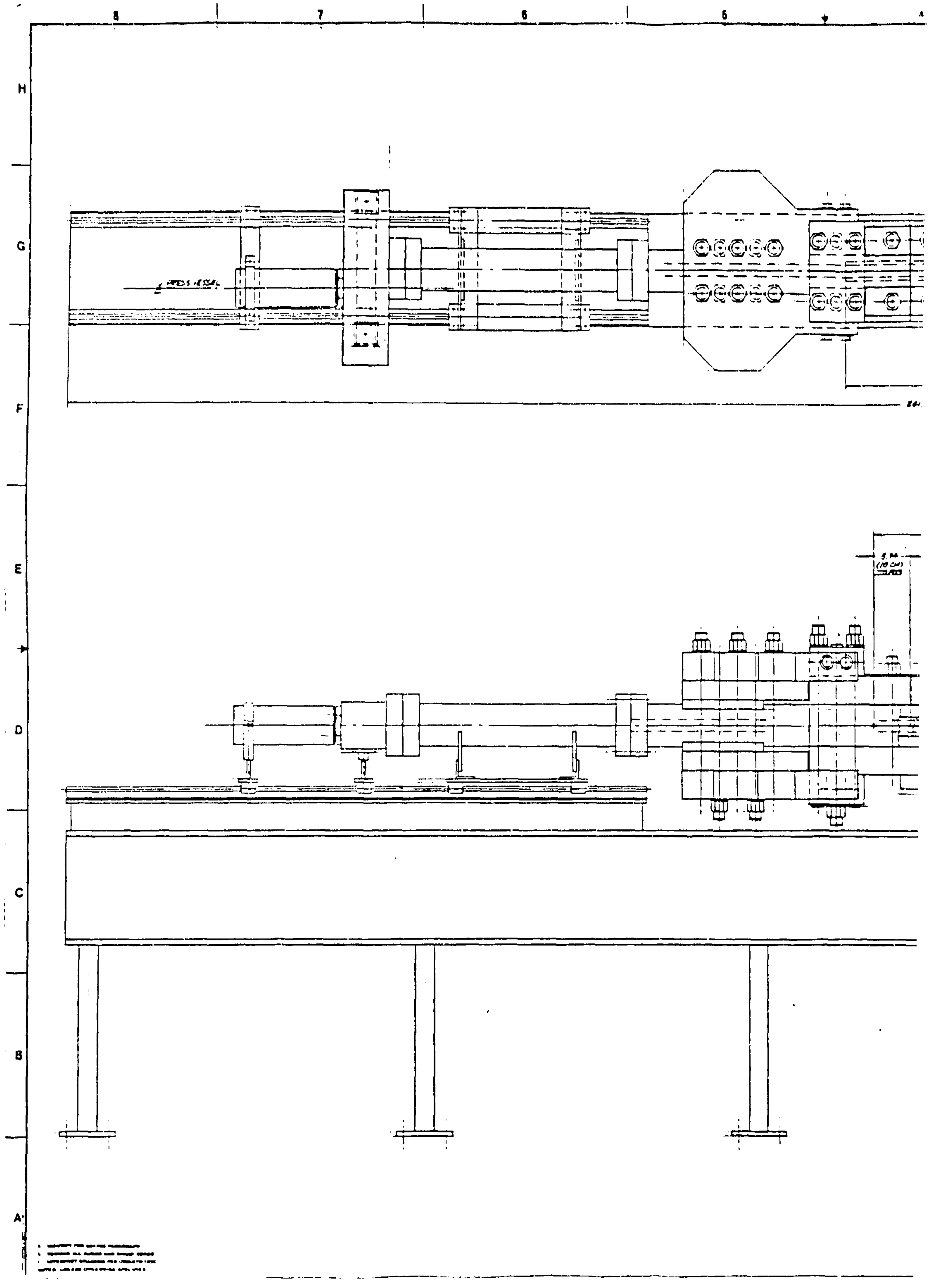
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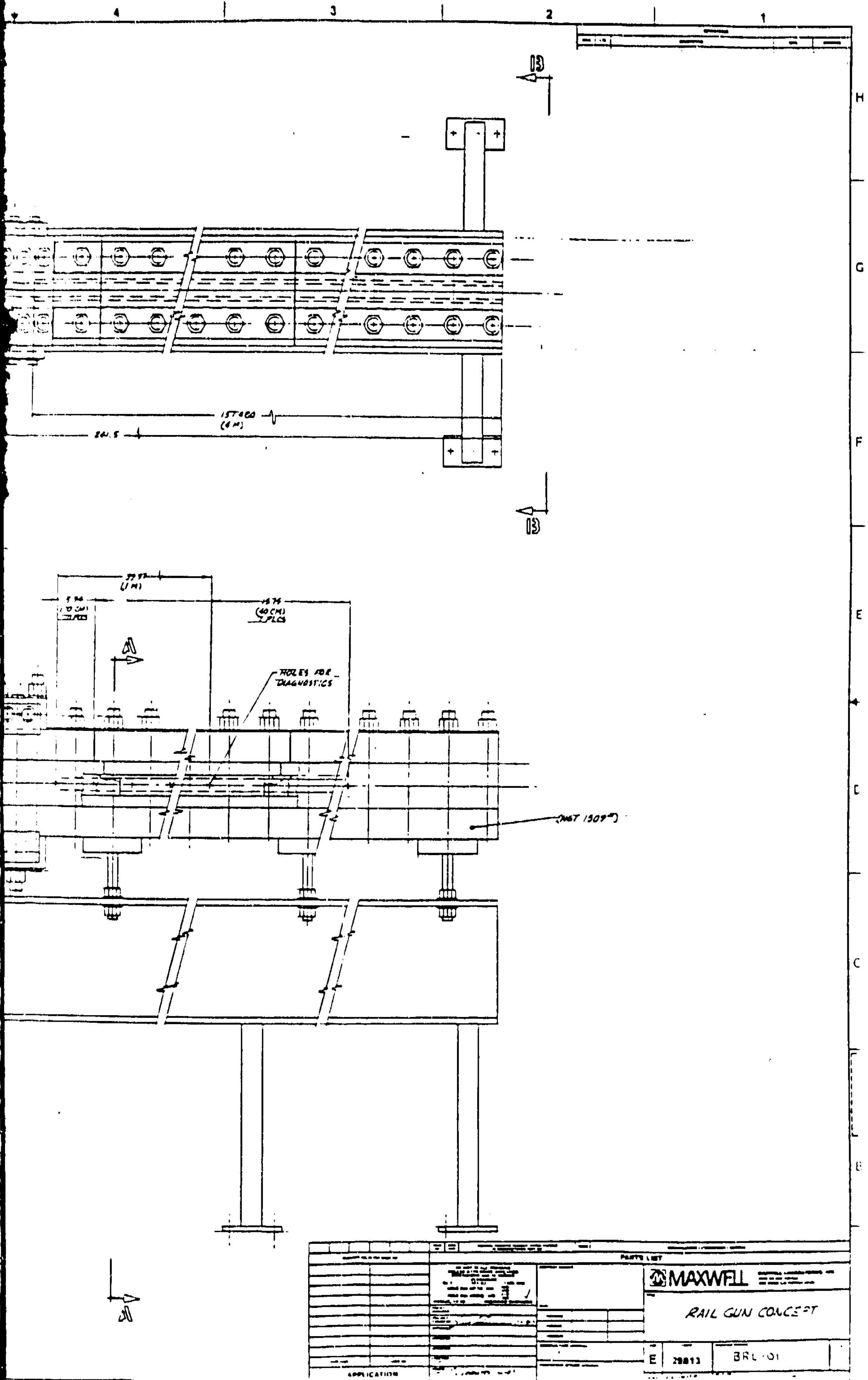
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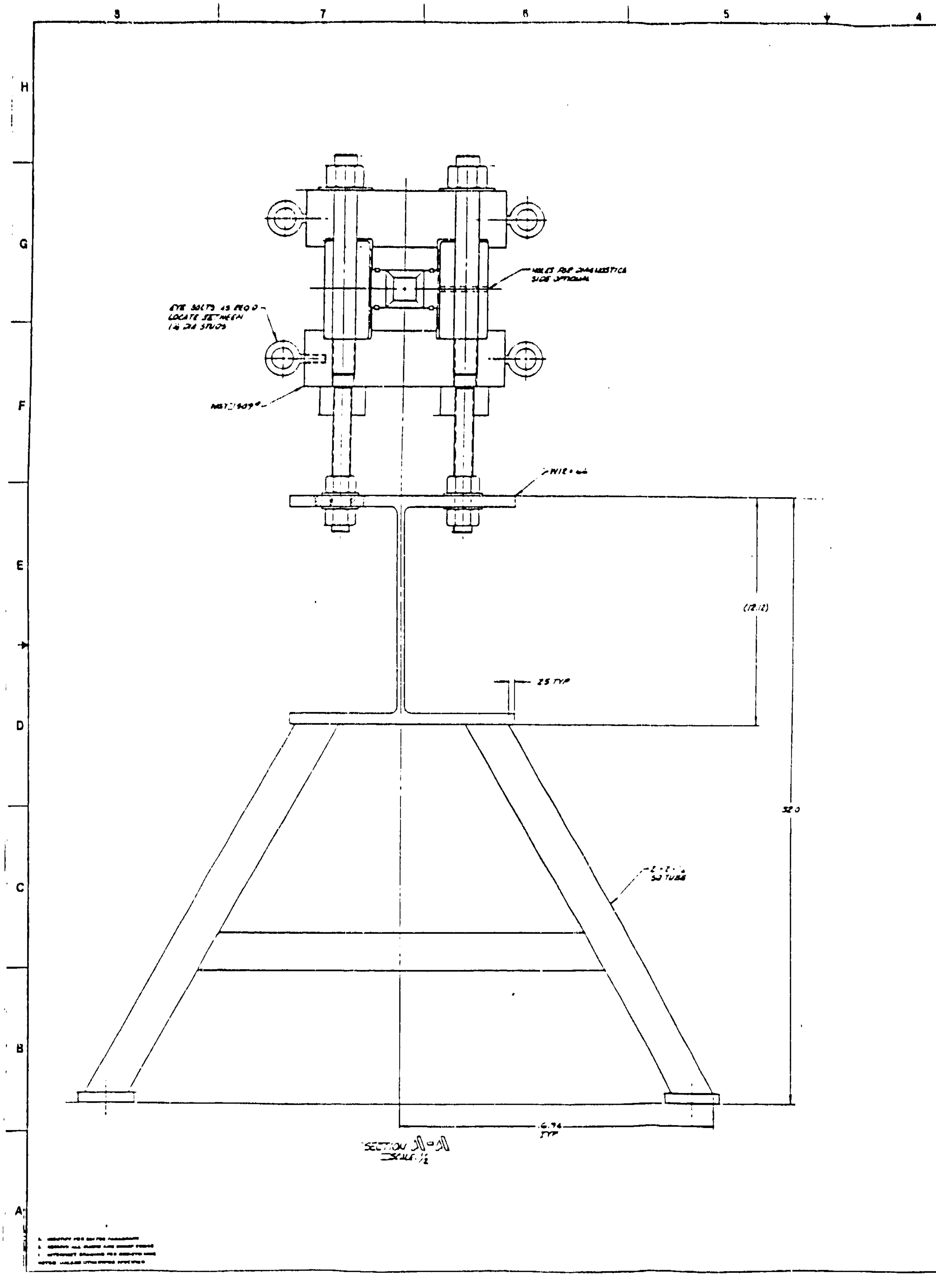

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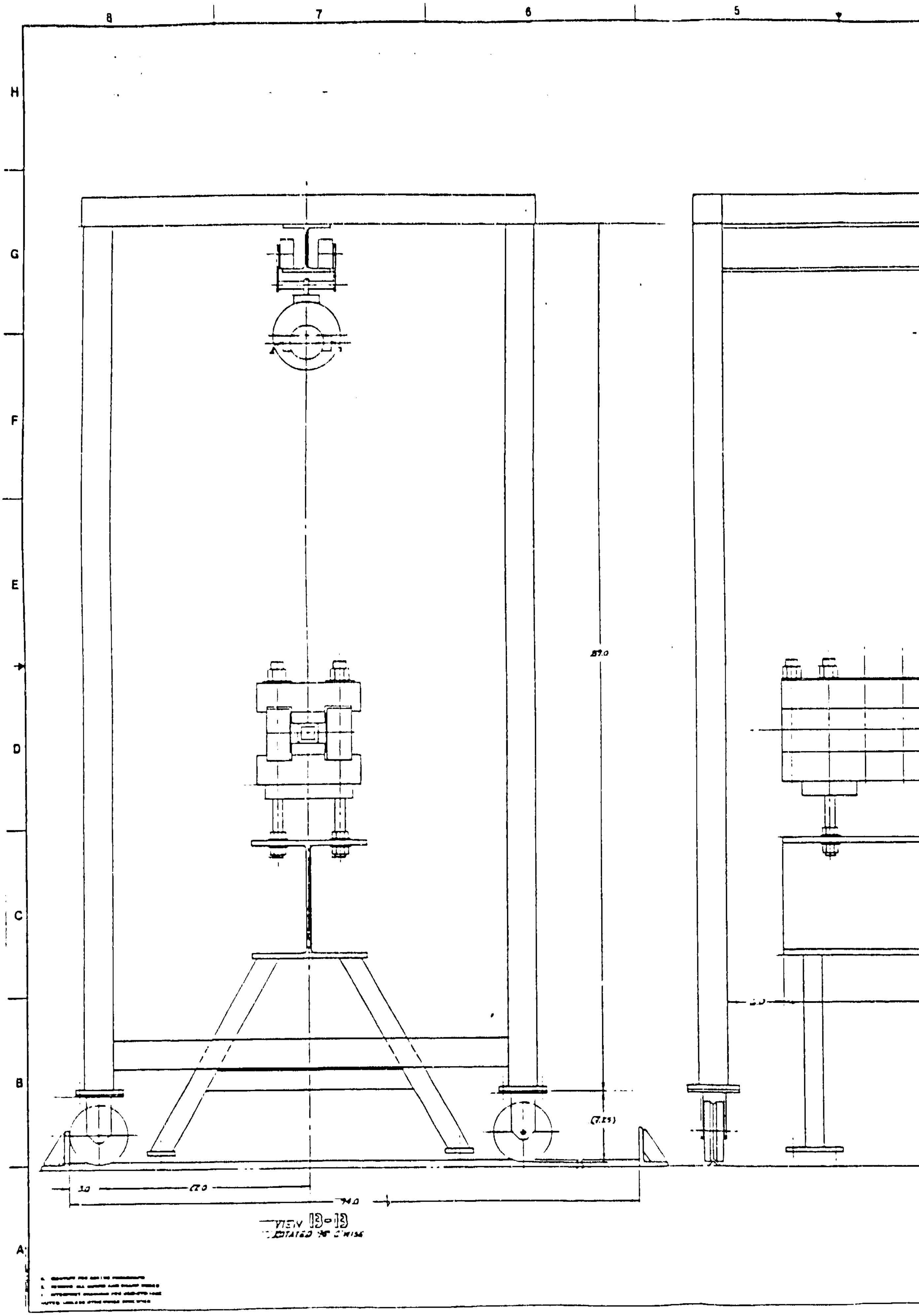

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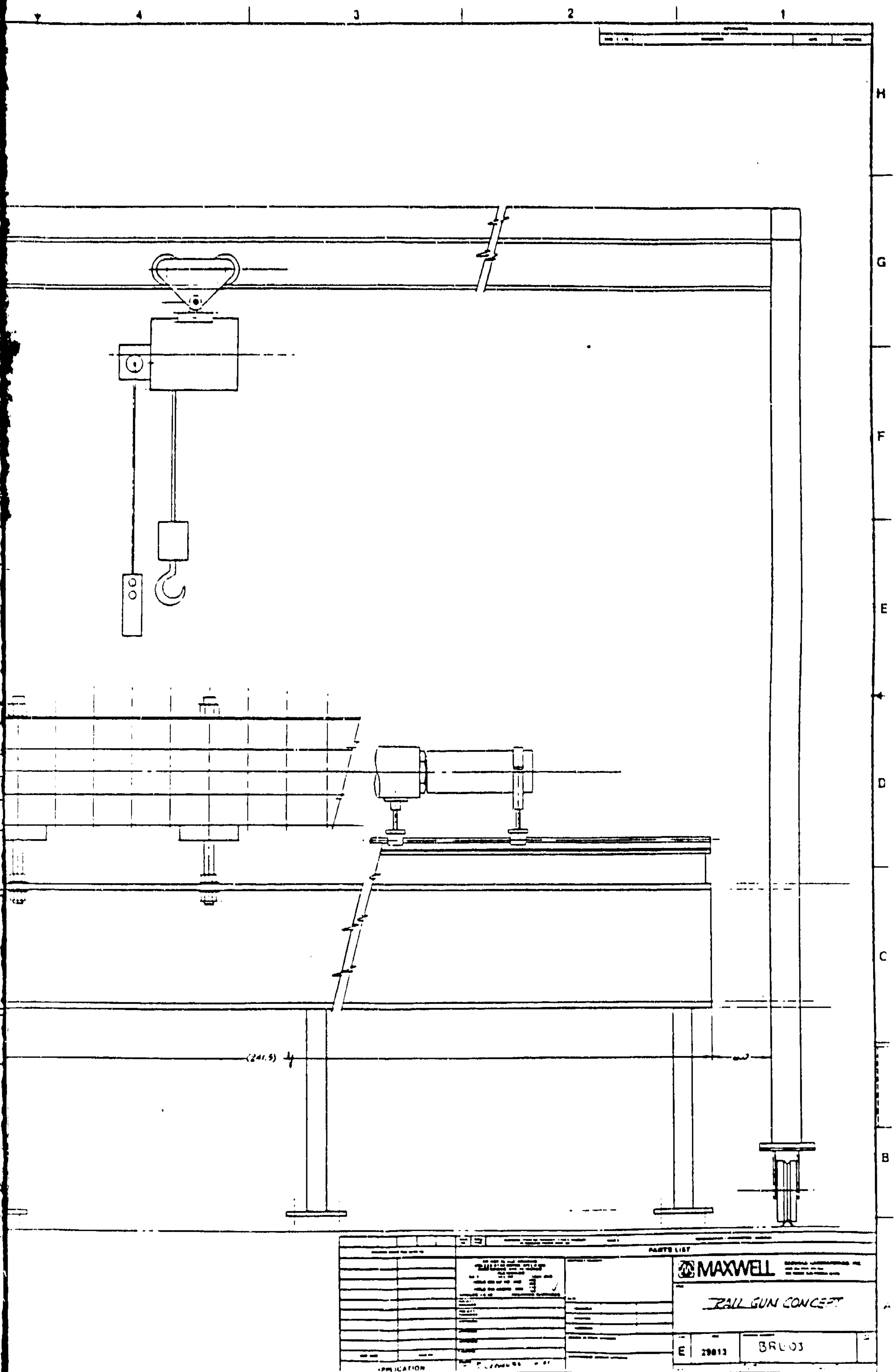

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